NASA Conference Publication 3166, Vol. 2

The Second Conference on Lunar Bases and Space Activities of the 21st Century

NASA Conference Publication 3166, Vol. 2

The Second Conference on Lunar Bases and Space Activities of the 21st Century

W. W. Mendell, *Editor*
NASA Lyndon B. Johnson Space Center
Houston, Texas

Papers from a conference sponsored by
Lyndon B. Johnson Space Center and
the Lunar and Planetary Institute,
Houston, Texas, and held in
Houston, Texas
April 5–7, 1988

NASA

National Aeronautics and
Space Administration

Office of Management

Scientific and Technical
Information Program

1992

Associate Editors

John W. Alred
Eagle Engineering

Larry S. Bell
University of Houston

Mark J. Cintala
NASA Johnson Space Center

Thomas M. Crabb
Orbital Technologies Corp.

Robert H. Durrett
Marshall Space Flight Center

Ben R. Finney
University of Hawaii

H. Andrew Franklin
Bechtel National, Inc.

James R. French
JRF Engineering Services

Joel S. Greenberg
Princeton Synergetics Inc.

Robert D. MacElroy
NASA Ames Research Center

Wendell W. Mendell
NASA Johnson Space Center

Thomas H. Morgan
NASA Headquarters

David J. Norton
HARC/STAR

Ferolyn T. Powell
Life Systems, Inc.

Joseph C. Sharp
NASA Ames Research Center

Paul D. Spudis
Lunar and Planetary Institute

Lawrence A. Taylor
University of Tennessee

Gordon R. Woodcock
Boeing Aerospace

Harlan J. Smith

1924–1991

Advocates for lunar bases, professionals exploring the frontiers of astronomy, and enthusiasts for scientific investigation of the unknown all have lost a champion with the passing of Harlan J. Smith. As Director of McDonald Observatory for 26 years and as chairman of the Astronomy Department at the University of Texas at Austin for 15 years, Harlan's academic and scientific credentials are stellar. However, his inexhaustible energy and boundless enthusiasm for developing innovative approaches to astronomical research set him apart from the mainstream.

My only opportunity to work personally with Harlan came about during my studies of a permanent lunar base as a goal for the U.S. space program in the first decade of the twenty-first century. At the Johnson Space Center in the early 1980s, Mike Duke and I came to understand that any lunar base program needed a legitimate scientific component. (By the term "legitimate," we meant the program science could be advocated successfully on scientific grounds by scientists in scientific forums.) Mike formed an advisory group to help us think through the problems, and he asked Harlan to represent astronomy.

Harlan's reaction to the request was a healthy skepticism as to whether any large, manned space project could be seen by astronomers as a prudent investment in science. Nevertheless, he agreed to participate in order to ensure a knowledgeable representation of the views of astronomers.

Harlan worked with us at his usual high energy level and helped organize the Lunar Base Working Group, which met at Los Alamos in April 1984. The Report of the Working Group includes a thoughtful discussion of the advantages to making astronomical observations from the the lunar surface. In particular, the seismically stable lunar surface permits optical interferometry with microarcsecond angular resolution in the observational data. Bernie Burke developed the concept of the lunar optical interferometer.

As Harlan began to appreciate the unique qualities of the lunar environment for high-resolution, high-sensitivity optical observations and for wide-spectrum radio observations on the radio-quiet farside, he became not only an advocate but a champion of lunar-based astronomy.

Harlan was familiar with the need for persistence in advocating high-quality scientific projects. He helped organize a one-day workshop on lunar astronomy following the annual meeting of the American Astronomical Society in 1986. As I led off the meeting with a short talk on lunar base concepts, a young man in the front row asked, "If there is not going to be a lunar base for 20 years, why are we having this workshop now?" I turned to Harlan, who was sitting a few seats away, and asked when he had started talking about the Large Space Telescope (now called the Hubble). Harlan answered simply, "1962."

Harlan was ubiquitous and indefatigable in his advocacy. When he traveled to Moscow in late 1988, he wasted no time in bringing the Moon to Soviet scientists, most of whom had not considered a lunar base program. (In the Soviet Union, human exploration missions were discussed in the context of Mars landings within a paradigm established by Roald Sagdeev and his American colleague, Carl Sagan.)

In the spring of 1989, I met the Soviet planetary scientist Mikhail Marov and we discussed the relative merits of a manned lunar base and piloted missions to Mars as candidates for the next great step into space exploration. Mikhail was unfamiliar with the lunar base concepts although he knew Sagdeev's ideas well. When I saw Mikhail again at the International Space University session in Stras-

bourg in August 1989, he told me that he had written a "white paper" for the Soviet Academy of Sciences on a lunar strategy. It seems that after his conversation with me, he had spent two days with his dear friend, Harlan Smith, who had persuaded him of the logic of the lunar step.

When cancer manifested itself in his body, Harlan optimistically pursued experimental therapies, which proved to be more debilitating than he anticipated. Nevertheless, he traveled to scientific meetings and worked on new ideas whenever his energy level permitted it. He left us in the midst of spawning a concept to place an automated telescope on 20,000-foot Mt. Auconquilcha in the Andes to serve as a technology demonstration for a lunar instrument.

Those of us trying to support his efforts had trouble matching his schedule even in his last days. I hope to see that lunar telescope in action, and I hope to see it named after one of modern astronomy's staunchest proponents, Harlan J. Smith.

Wendell Mendell
Houston, Texas
November 20, 1991

CONTENTS

Prologue xiii

Acknowledgments xvii

VOLUME 1

1 / LUNAR TRANSPORTATION SYSTEMS

Conceptual Analysis of a Lunar Base Transportation System 3
T. D. Hoy, L. B. Johnson III, M. B. Persons, and R. L. Wright

Lunar Base Mission Technology Issues and Orbital Demonstration Requirements on Space Station 17
C. P. Llewellyn and D. J. Weidman

Adaption of Space Station Technology for Lunar Operations 25
J. M. Garvey

Operational Considerations for Lunar Transportation 31
A. J. Petro

Electric Propulsion for Lunar Exploration and Lunar Base Development 35
B. Palaszewski

Advanced Propulsion for LEO-Moon Transport: I. A Method for Evaluating Advanced Propulsion Performance 47
M. O. Stern

Advanced Propulsion for LEO-Moon Transport: II. Tether Configurations in the LEO-Moon System 55
J. R. Arnold and W. B. Thompson

Advanced Propulsion for LEO-Moon Transport: III. Transportation Model 61
M. W. Henley

Enabling Lunar and Space Missions by Laser Power Transmission 69
R. J. De Young, J. E. Nealy, D. H. Humes, and W. E. Meador

Lunar 3He, Fusion Propulsion, and Space Development 75
J. F. Santarius

The Transportation Depot—An Orbiting Vehicle Support Facility 83
M. Kaszubowski and J. K. Ayers

Developing a Safe On-Orbit Cryogenic Depot 95
N. J. Bahr

Lunar Lander Stage Requirements Based on the Civil Needs Data Base 101
J. A. Mulqueen

Lunar Lander Conceptual Design 119
J. M. Stecklein, A. J. Petro, W. R. Stump, A. S. Adorjan, T. V. Chambers, M. D'Onofrio, J. K. Hirasaki, O. G. Morris, G. Nudd, R. P. Rawlings, C. C. Varner, C. W. Yodzis, and S. J. Zimprich

Preliminary Definition of a Lunar Landing and Launch Facility (Complex 39L) 133
H. D. Matthews, E. B. Jenson, and J. Linsley

Lunar Base Launch and Landing Facilities Conceptual Design 139
P. G. Phillips, C. H. Simonds, and W. R. Stump

2 / LUNAR BASE SITE SELECTION

The Choice of the Location of the Lunar Base 155
V. V. Shevchenko

Geological and Geophysical Field Investigations from a Lunar Base at Mare Smythii 163
P. D. Spudis and L. L. Hood

A Lunar Polar Expedition 175
R. Dowling, R. L. Staehle, and T. Svitek

Astronomy on the Moon: Geological Considerations 183
G. J. Taylor

Helium Mining on the Moon: Site Selection and Evaluation 189
E. N. Cameron

The Lunar Orbital Prospector 199
F. J. Redd, J. N. Cantrell, and G. McCurdy

Lunar Observer Laser Altimeter Observations for Lunar Base Site Selection 209
J. B. Garvin and J. L. Bufton

A Search for Intact Lava Tubes on the Moon: Possible Lunar Base Habitats 219
C. R. Coombs and B. R. Hawke

A Seismic Risk for the Lunar Base 231
J. Oberst and Y. Nakamura

3 / LUNAR SURFACE ARCHITECTURE AND CONSTRUCTION

Lunar Architecture and Urbanism 237
B. Sherwood

Earth-Based Analogs of Lunar and Planetary Facilities 243
L. Bell and G. Trotti

Inflatable Habitation for the Lunar Base 249
M. Roberts

Preliminary Design Study of Lunar Housing Configurations 255
K. H. Reynolds

Prefabricated Foldable Lunar Base Modular Systems for Habitats, Offices, and Laboratories 261
Y. Hijazi

Concrete Lunar Base Investigation 267
T. D. Lin, J. Senseny, L. D. Arp, and C. Lindbergh

Vertical Regolith Shield Wall Construction for Lunar Base Applications 275
J. Kaplicky, D. Nixon, and J. Wernick

Evolving Concepts of Lunar Architecture: The Potential of Subselene Development 281
A. W. Daga, M. A. Daga, and W. R. Wendel

Lunar Subsurface Architecture Enhanced by Artificial Biosphere Concepts 293
J. D. Klassi, C. J. Rocha, and C. A. Carr

Extraterrestrial Applications of Solar Optics for Interior Illumination 299
D. A. Eijadi and K. D. Williams

4 / SCIENTIFIC INVESTIGATIONS AT A LUNAR BASE

The Roles of Humans and Robots as Field Geologists on the Moon 307
P. D. Spudis and G. J. Taylor

Some Astronomical Challenges for the Twenty-first Century 315
J. O. Burns

Radio Astrometry from the Moon 321
R. P. Linfield

Required Technologies for Lunar Astronomical Observatories 323
S. W. Johnson and J. P. Wetzel

Environmental Effects on Lunar Astronomical Observatories 329
S. W. Johnson, G. J. Taylor, and J. P. Wetzel

Lunar Base Activities and the Lunar Environment 337
R. R. Vondrak

An Artificially Generated Atmosphere Near a Lunar Base 347
J. O. Burns, I. Fernini, M. Sulkanen, N. Duric, G. J. Taylor, and S. W. Johnson

A Manned Exobiology Laboratory Based on the Moon 351
C. W. Gehrke, C. Ponnamperuma, K. C. Kuo, J. E. McEntire, D. L. Stalling, and R. W. Zumwalt

Possible Biomedical Applications and Limitations of a Variable-Force Centrifuge on the Lunar Surface: A Research Tool and an Enabling Resource 353
K. L. Cowing

APPENDIXES

Author Index A-1

Subject Index A-3

Location Index A-23

Acronym Glossary A-25

VOLUME 2

5 / UTILIZATION OF LUNAR RESOURCES

Resources for a Lunar Base: Rocks, Minerals, and Soil of the Moon 361
L. A. Taylor

The Formation of Ore Mineral Deposits on the Moon: A Feasibility Study 379
L. A. Taylor and F. Lu

Applications for Special-Purpose Minerals at a Lunar Base 385
D. W. Ming

Water and Cheese from the Lunar Desert: Abundances and Accessibility of H, C, and N on the Moon 393
L. A. Haskin

First Steps to Lunar Manufacturing: Results of the 1988 Space Studies Institute Lunar Systems Workshop 397
G. E. Maryniak

Lunar Resource Recovery: A Definition of Requirements 407
D. Elsworth, J. L. Kohler, and S. S. Alexander

Electrolytic Smelting of Lunar Rock for Oxygen, Iron, and Silicon 411
L. A. Haskin, R. O. Colson, D. J. Lindstrom, R. H. Lewis, and K. W. Semkow

Lunar Mining of Oxygen Using Fluorine 423
D. M. Burt

Uses of Lunar Sulfur 429
D. Vaniman, D. Pettit, and G. Heiken

Availability of Hydrogen for Lunar Base Activities 437
R. Bustin and E. K. Gibson Jr.

The Influence of Lunar Propellant Production on the Cost-Effectiveness of Cislunar Transportation Systems 447
H. H. Koelle

Impact of Lunar Oxygen Production on Direct Manned Mars Missions 453
R. M. Young Jr. and W. B. Tucker

Fusion Energy from the Moon for the Twenty-first Century 459
G. L. Kulcinski, E. N. Cameron, J. F. Santarius, I. N. Sviatoslavsky, L. J. Wittenberg, and H. H. Schmitt

Synergism of ^{3}He Acquisition with Lunar Base Evolution 475
T. M. Crabb and M. K. Jacobs

Physical Properties of Concrete made with Apollo 16 Lunar Soil Sample 483
T. D. Lin, H. Love, and D. Stark

The Possibility of Concrete Production on the Moon 489
N. Ishikawa, H. Kanamori, and T. Okada

Concrete Structure Construction on the Moon 493
S. Matsumoto, H. Namba, Y. Kai, and T. Yoshida

Lunar Concrete for Construction 497
H. S. Cullingford and M. D. Keller

6 / LIFE SUPPORT AND CREW HEALTH AT A LUNAR BASE

The Environmental Control and Life-Support System for a Lunar Base—What Drives its Design 503
W. D. Hypes and J. B. Hall Jr.

Life Systems for a Lunar Base 513
M. Nelson, P. B. Hawes, and M. Augustine

Lunar Base CELSS—A Bioregenerative Approach 519
G. W. Easterwood, J. J. Street, J. B. Sartain, D. H. Hubbell, and H. A. Robitaille

Crop Growth and Associated Life Support for a Lunar Farm 525
T. Volk and H. Cullingford

Long-Term Lunar Stations: Some Ecological Considerations 531
B. Maguire Jr. and K. W. Scott

Engineering Verification of the Biomass Production Chamber 537
R. P. Prince, W. M. Knott III, J. C. Sager, and J. D. Jones

Scenarios for Optimizing Potato Productivity in a Lunar CELSS 543
R. M. Wheeler, R. C. Morrow, T. W. Tibbitts, and R. J. Bula

Potential of Derived Lunar Volatiles for Life Support 547
R. J. Bula, L. J. Wittenberg, T. W. Tibbitts, and G. L. Kulcinski

Technology Development for Lunar Base Water Recycling 551
J. R. Schultz and R. L. Sauer

Plasma Reactor Waste Management Systems 559
R. O. Ness Jr., J. R. Rindt, and S. R. Ness

Distribution of Human Waste Samples in Relation to Sizing Waste Processing in Space 563
D. Parker and S. K. Gallagher

Bone Loss and Human Adaptation to Lunar Gravity 569
T. S. Keller and A. M. Strauss

7 / OPERATIONS AND INFRASTRUCTURE ON THE LUNAR SURFACE

Conceptual Design of a Lunar Base Thermal Control System 579
L. C. Simonsen, M. J. DeBarro, and J. T. Farmer

Advanced Photovoltaic Power System Technology for Lunar Base Applications 593
D. J. Brinker and D. J. Flood

Solar Water Heating System for a Lunar Base 597
R. E. Somers and R. D. Haynes

Automation and Robotics Considerations for a Lunar Base 603
N. E. Sliwa, F. W. Harrison Jr., D. I. Soloway, W. S. McKinney Jr., K. Cornils, W. R. Doggett, E. G. Cooper, and T. E. Alberts

Lunar Surface Mining for Automated Acquisition of Helium-3: Methods, Processes, and Equipment 609
Y. T. Li and L. J. Wittenberg

The Lunar Roving Vehicle—A Historical Perspective 619
S. Morea

Mobile Work Platform for Initial Lunar Base Construction 633
J. W. Brazell, B. K. McLaren, G. V. McMurray, and W. M. Williams

Engineering Planetary Lasers for Interstellar Communication 637
B. Sherwood, M. J. Mumma, and B. K. Donaldson

Unit Operations for Gas-Liquid Mass Transfer in a Reduced-Gravity Environments 647
D. R. Pettit and D. T. Allen

Combustion of Gaseous Fuels Under Reduced-Gravity Conditions 653
M. Y. Bahadori and R. B. Edelman

Occupational Ergonomics in Space 659
J. Stramler

8 / ENABLING A PROGRAM FOR HUMAN EXPLORATION OF SPACE

The Real World and Lunar Base Activation Scenarios 667
H. H. Schmitt

Moon Park: A Research and Educational Facility 673
K. Kuriki, T. Saito, and Y. Ogawa

Lunar Stepping Stones to a Manned Mars Exploration Scenario 677
W. L. Davidson and W. R. Stump

Creating a Foundation for a Synergistic Approach to Program Management 683
K. T. Knoll

The "Province" and "Heritage" of Mankind Reconsidered: A New Beginning 691
J. I. Gabrynowicz

A Basis of Settlement: Economic Foundations of Permanent Pioneer Communities 697
E. M. Jones

The Lunar "Community Church": Contributions to Lunar Living and to Evolution of Ethical and Spiritual Thinking 703
J. H. Allton

APPENDIXES

Author Index A-1

Subject Index A-3

Location Index A-23

Acronym Glossary A-25

Prologue

Plans for manned bases on the Moon were first conducted by professional engineering organizations in the late 1950s as part of Project Horizon, a classified study sponsored by the U.S. Department of the Army. The civilian space program began to think about such things after President Kennedy's directive to land a man on the lunar surface by the end of the decade. Within a few years, NASA was working on concepts for extended human presence on the Moon under the Apollo Applications Program, as a continuation of the Apollo initiative. Journeys to Mars were also mapped out in the EMPIRE studies funded by NASA.

Detailed plans for lunar bases were simultaneously being developed in the Soviet Union as part of their secret manned lunar program. Although details of the Soviet N-1 rocket and their lunar transportation system have been released publicly, their lunar base plans have not yet been discussed.

In 1969-70, the Nixon Administration commissioned a study of the future of the space program under the stewardship of Vice-President Agnew. The report of the Space Task Group (STG) presented a sequence of manned programs, beginning with a low Earth orbit space station and continuing on to bases on the surface of the Moon and on Mars. The plan offered three different levels of effort with schedules dependent on funding commitments. In outline, the Space Task Group Report strongly resembles the current Space Exploration Initiative.

President Nixon and his staff decided that budgetary constraints would not permit commitment to a long-range program of human exploration of the solar system. In fact, they canceled the final two missions of the ongoing Apollo program. NASA conducted the Skylab program and the Apollo-Soyuz Test Project with spare Apollo hardware, but the long-range plans of the space agency were reduced to the development of the reusable space shuttle. In the STG Report, the Earth-to-orbit cargo vehicle, which later became the shuttle, had not received major emphasis. In NASA of the 1970s, it became the center of focus in the manned program and was to have major impacts on the unmanned program also.

The 1970s also saw a sequence of presidents who did not assign a high priority to ambitious goals for the space program. The NASA administrators reflected this philosophy and concentrated on being "team players" in restricted budgetary environments. The situation can be illustrated by considering the fiscal projections published in the STG Report for their three proposed approaches to expanding human presence in space. The graph that contained the funding estimates also featured a dotted line running along the bottom part of the chart. This dotted line was included to give the reader a reference point for the funding levels reflecting a hypothetical elimination of the manned space program. Looking back on the actual NASA funding (in constant year dollars) for the decade of the 1970s, we can see that it fell approximately 20% below the hypothetical dotted line.

Struggling to keep fiscal body and soul together, NASA invested few resources in true strategic planning. The last lunar base studies of the Apollo era have publication dates of 1972 or 1973. The agency looked seriously at solar power satellites as solutions to the energy crisis and dabbled in the space colony phenomenon, but generally the organizational mind-set embraced incremental programmatic evolution rather than bold landscapes with new initiatives. The phasing out of one major engineering development program (the space shuttle) and the start-up of another (the space station) occupied all the energy of the policy process within NASA of the early 1980s.

The space shuttle was operated by the Office of the National Space Transportation System (NSTS), a designation that could encompass other elements such as a space station and orbital transfer vehicles (OTV) for launching payloads from LEO to higher orbits. At the inauguration of the Reagan Administration, configurations for a LEO space station were being explored, and the performance requirements for a future OTV were being inserted into NASA databases.

This was the state of planning that I and my colleagues found in 1981 when we set off to explore the possibility of launching a Lunar Polar Orbiter (LPO) mission on the (then) new space shuttle. As NASA scientists involved in planetary exploration, we had little familiarity with manned programs. We were interested in resuming exploration of the Moon with implementation of the rather simple LPO spacecraft that had been "under consideration" for almost 10 years.

From our point of view, the NSTS, in its configuration circa the year 2000, appeared to provide routine access to the Moon. An OTV designed to deliver a communications satellite from the space station to geostationary orbit should be able to take satellites (or even landers) to the Moon because the ΔV (change in orbital velocity) required for both missions was essentially the same. As we pursued the matter further, we wondered whether consideration should be given to sizing the NSTS to carry humans and supporting cargo to the Moon for a lunar base.

Within NASA we encountered a number of reasons why a lunar base was a bad idea. A lunar base would be unaffordable or would compete with the space station; or Congress might scuttle the space station if it was believed to be a precursor for a lunar base. As we insisted on closer examination of an obvious extrapolation of the Space Transportation System, we became known as "lunar base advocates." We were told that advocacy of any particular objective was improper. The job of NASA planning was to produce a comprehensive list of all possible futures and study each to the same level of (superficial) detail as "options."

In 1983 we began a process to which I now refer as the legitimization of the lunar base discussion. We perceived the need to create forums wherein individuals and groups with accepted credentials could raise the relevant questions. Thereby the subject could become legitimate to evaluate within NASA. Critical steps in that process were the Report of the Lunar Base Working Group, from a workshop held at Los Alamos in April 1984, and the book *Lunar Bases and Space Activities of the 21st Century,* which recorded the proceedings of a symposium held at the National Academy of Sciences in Washington, DC, in October 1984. These meetings were conceived and organized by a small group of aerospace leaders from government, industry, and academia, who had been attracted to the lunar base as a long-term policy objective. Within NASA, funding was secured with the help of Deputy Administrator Hans Mark.

From that time forward, the planning environment evolved rapidly. A working group internal to NASA completed in 1985 a review of the technical constraints for manned Mars missions. The National Commission on Space delivered to the President in early 1986 a vision for the next 50 years. Astronaut Sally Ride led a NASA Task Group to produce the influential report, Leadership and America's Future in Space. NASA formed an Office of Exploration, staffed to the Administrator, in 1987. All these study groups relied heavily on technical information developed primarily at the Johnson Space Center a year or two earlier when lunar bases were not de rigeur. That work was performed on a tiny budget, but had the explicit support of Center Directors Chris Kraft and Aaron Cohen.The Second Symposium on Lunar Bases and Space Activities of the 21st Century was convened when interest in permanent presence on the Moon was growing rapidly. The Office of Exploration had become a funding source for new studies, replacing updated versions of older work. Internal funds in various organizations were being used to evaluate fresh ideas. New faces were appearing at aerospace meetings, particularly from the constructor-engineer companies, which possess unique and valuable expertise in building and operating facilities in harsh and isolated environments.

The current volume consists of a peer-reviewed selection of the papers delivered at the Second Symposium, held in Houston, Texas, on April 5-7, 1988. Compared to the 1984 symposium on lunar bases, these papers tend to go into more technical depth, reflecting a higher content of currently funded research. Participation from NASA is higher. Like the first symposium, the subject matter covers a broad range of topics, including discussions beyond the usual bounds of engineering and science. The selections are representative of the level of planning during the first year of operation of NASA's Office of Exploration.

During the preparation of this volume, many changes have occurred in what is now called the Space Exploration Initiative (SEI); and some of the assumptions in the papers here are dated. Legitimization of the lunar base concept has been completed with President Bush's sweeping vision of a return to the Moon ("... this time to stay...") followed by piloted missions to Mars. At this writing, the fate of Space Station Freedom is uncertain, and progress in planning the SEI is awaiting the report from the Synthesis Group led by General Tom Stafford. The Report of the Advisory Committee on the Future of the Space Program is being cited and debated throughout the aerospace community.

Impatient enthusiasts supporting the human exploration of the solar system despair over the current turmoil. However, we must remind ourselves of the enormous progress that has been made in creating a real dialogue within the American body politic on the promise of the space frontier. This vision of the future must not be trivialized by identifying it with any single program or mission. Our movement to the planets must be made on a broad front with the active involvement and participation from many institutions in our society and from many of the peoples of the world. No longer is it sufficient to concentrate all space activities in one organization and expect all other constituencies to support it. Yet fundamental change in the assignment of responsibility and authority is neither easy nor self-evident. We now are seeing the beginnings of change to a "new space order" that must be established before we can "boldly go where no one has gone before."

Wendell Mendell
Houston, Texas
May 23, 1991

Acknowledgements

Providing peer review for a collection of professional papers is always a demanding task for an editor. He must find associate editors—responsible and knowledgeable volunteers each of whom is willing to take charge of six to eight manuscripts and solicit qualified referees for them. In an eclectic volume such as this one, the editorial board must span a variety of disciplines and professional communities. Every community has its own culture and standards for judging worth, and these value systems must be integrated to provide a uniform quality to the finished collection.

For this volume, I was forced to go to 17 associate editors in order to provide reasonable workloads for each one, and I am grateful to them all; but I feel particularly obligated to Gordon Woodcock, Larry Taylor, and John Alred, all of whom jumped in at crucial times.

I thank Stephanie Tindell, Sarah Enticknap, Ronna Hurd, and other members of the Publications Services Department at the Lunar and Planetary Institute for exhibiting inexhaustible patience throughout the production phase. Bill Lagle from the Lockheed Engineering Services Company was invariably eager to do whatever was asked, and I should have taken advantage of his talents more often. Mark Cintala and Sarah Enticknap deserve special acknowledgment for creating the subject index.

Finally, I must acknowledge the efforts of Mike Duke and Barney Roberts in holding the original symposium and in helping to publish this book.

Wendell Mendell
Houston, Texas
February 7, 1992

5 / Utilization of Lunar Resources

RESOURCES FOR A LUNAR BASE: ROCKS, MINERALS, AND SOIL OF THE MOON

N93-13973

Lawrence A. Taylor

Department of Geological Sciences
The University of Tennessee
Knoxville TN 37996-1410

The rocks and minerals of the Moon will be included among the raw materials used to construct a lunar base. The lunar regolith, the fragmental material present on the surface of the Moon, is composed mostly of disaggregated rocks and minerals, but also includes glassy fragments fused together by meteorite impacts. The finer fraction of the regolith (i.e., <1 cm) is informally referred to as soil. The soil is probably the most important portion of the regolith for use at a lunar base. For example, soil can be used as insulation against cosmic rays, for lunar ceramics and abodes, or for growing plants. The soil contains abundant solar-wind-implanted elements as well as various minerals, particularly oxide phases, that are of potential economic importance. For example, these components of the soil are sources of oxygen and hydrogen for rocket fuel, helium for nuclear energy, and metals such as Fe, Al, Si, and Ti.

INTRODUCTION

Based upon the nine lunar sample return missions (six from Apollo, three from Luna), we have over 380 kg (almost 840 lb) of returned lunar samples and an excellent knowledge of the nature of the rocks and regolith over a limited portion of the Moon's frontside. These are the raw materials that a lunar base can utilize. They may also be the source of certain products with which to help justify such an ambitious endeavor, e.g., ^3He, hydrogen, oxygen, Fe metal.

There have been many excellent reviews of the mineralogy and petrology of the returned lunar samples, among which the books by *Ross Taylor* (1975, 1982) are paramount. In addition, there are several fine review articles from which I have drawn liberally (e.g., *Smith,* 1974; *Frondel,* 1975; *Papike et al.,* 1976, 1982; *Smith and Steele,* 1976; *Papike and Bence,* 1979; *Wilhelms,* 1984). I shall not attempt to repeat what has been so well written previously. Instead, I will present a brief synopsis of the basic petrology and mineralogy of the lunar samples, with particular attention to those aspects that may be of significance for lunar exploitation.

With respect to the possible future use of lunar materials, the recent publication by the Lunar and Planetary Institute (Houston), *Lunar Bases and Space Activities of the 21st Century* (1985), is essential. In addition, a book entitled *Lunar Sourcebook* (1991), coordinated through the Lunar and Planetary Institute and published by Cambridge University Press, summarizes our current knowledge of the Moon, which will be important for future lunar base endeavors.

In addition to the nature of lunar components, a listing of catalogs and documents on lunar samples, organized by mission, has been compiled and is presented in this paper. With certain studies designed to utilize lunar materials, it may be necessary to actually experiment with lunar samples. A brief outline is given that should be followed in order to apply for lunar samples for engineering or industrial investigations.

CONDITIONS OF ROCK AND MINERAL FORMATION

The Earth and its moon differ significantly in the environments at their surfaces and also in the formation conditions of their rocks, minerals, and soils. Because of its smaller mass and, hence, escape velocity, the Moon cannot maintain a significant atmosphere ($<10^{-7}$ torr) with the result that it has no "insulating blanket" that would (1) aid the retention of solar energy and (2) shield it from cosmic rays, solar wind, and meteoritic and cometary infall. Consequently, the surface of the Moon undergoes tremendous changes in temperature (+135°C to -130°C), and meteorites (from kilometers to submicron sizes) have bombarded the surface continually for aeons at fantastic speeds (e.g., 40,000-250,000 km/hr). These meteorite impacts result in the only effective process of weathering and erosion on the Moon. Also, because of the complete lack of any water, chemical weathering, so dominant on Earth, is nonexistent on the lunar surface. Therefore, the meteorite components, principally the minerals, are discernable and add a significant chemical signature to the soil. In addition, the solar-wind-implanted particles, notably protons (hydrogen), helium, and carbon, introduce exogenous components into the soil. These particles and meteorite and micrometeorite impacts, with their associated shock metamorphism, including complete melting, ultimately produce one of the distinctive aspects of lunar soil, namely the presence of "agglutinates" (aggregates of rock and mineral fragments and glass) with their myriad minute iron metal (i.e., Fe^0) grains.

The formation conditions of lunar rocks, most notably the volcanic ones, are different from those on Earth in two basic aspects: (1) temperatures of formation and (2) the oxygen partial pressures prevailing during formation. Largely because of the lack of water and its great "fluxing" ability and the paucity of other mineralizers (e.g., F, Cl), the crystallization temperatures of the mineral components of the rocks are about 100°-150°C higher than corresponding ones on Earth. The conditions of oxygen

partial pressure (called oxygen fugacity; abbreviated as fO_2) are distinctly different (Fig. 1) and have a pronounced effect on the mineralogy. Because of the low oxygen fugacity, there is no Fe^{3+} present in any of the minerals. Indeed, because the formation conditions are at and below the iron/wüstite buffer curve, native Fe is ubiquitous in lunar samples of all kinds. Likewise, some of the elements in the minerals are present in a reduced state with unusual valance states compared to Earth situations (e.g., Ti^{3+} vs. Ti^{4+}; Cr^{2+} vs. Cr^{3+}; Fe^0 vs. Fe^{2+}; P^{3+} vs. P^{5+}.

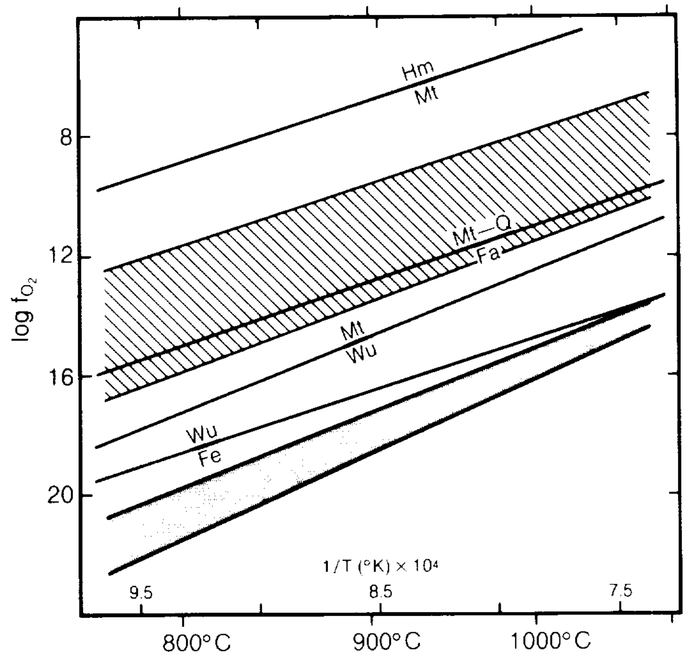


Fig. 1. Partial pressure of oxygen (fO_2) vs. temperature plot depicting the regions for terrestrial (upper shaded area) and lunar (lower area) magmatic activity. The terrestrial region centers around the fayalite/quartz + magnetite buffer curve, whereas the lunar activity is located entirely below the Fe/wüstite curve, in the field where metallic Fe is stable. No highly oxidized Fe (i.e., Fe^{3+}) is stable within this lunar area.

ROCKS

Most U.S. Apollo (manned) and Russian Luna (unmanned) missions landed within maria, areas of comparatively young basalt flows. Some missions were to areas consisting largely of highland rocks. Several excellent review papers have been written concerning the lunar rock, among them *Papike and Bence* (1979), *Papike and Vaniman* (1978), *Smith and Steele* (1976), *Taylor* (1975, 1982), and *Wilhelms* (1984). Therefore, the discussion presented here will be brief. An additional reason for this shortened portion on rocks is that it is the minerals that are of most importance for lunar base endeavors, not the rocks per se.

Representative portions of the ancient highlands have been sampled by Apollo 14, Apollo 16, and Luna 20. However, every mission brought back some samples identified as originating in the highlands. Although it appears that the darker maria make up a substantial portion of the surface, mare basalts only constitute between 15% and 20% of the Moon. The rocks on the Moon consist of two basic types: igneous rocks, formed through processes of crystallization of minerals from a silicate melt, and breccias, created as a result of meteorite impacts whereby preexisting rocks are broken and mixed with other rocks and soil and shock metamorphosed into coherent, cemented aggregates. Indeed, few of the highland samples returned to Earth are simple igneous rocks. Most consist of complex metamorphosed breccias, remelted regolith, or fine-grained soil.

The igneous rocks consist of mare basalts, iron-rich lava flows that filled the great impact basins, and the plutonic rocks of the highlands, composed of anorthosites, norites, and troctolites. In addition, there is a chemical component called KREEP (an acronym for the elements K, REE, and P) that is present in some basalts and that dominates trace-element patterns of most highland polymict breccias.

The mare basalts have been classified into various types based upon their mineralogy and bulk chemistry. There are three general mare basalt types, high-Ti, low-Ti, and very-low-Ti (VLT) basalts, and some less abundant varieties such as very-high-potassium (VHK) basalt. Figure 2 shows the variations in chemistry for the three main types. These can be seen best in the TiO_2 vs. Mg′ [called "magnesium number" and equal to atomic Mg/(Mg+Fe)]. These rocks possess low contents of the volatile elements Na and K, a distinction from most terrestrial basalts. Pyroxene makes up about 50% by volume of the basalts, regardless of type, with 20-30% plagioclase, and 0-20% olivine. The opaque oxide phases, ilmenite and chromite-ulvöspinel, vary from a few percent to over 20%. The ubiquitous native Fe is present in amounts less than 1%. (Note: "modal percent" refers to the volume percent actually present in the rock; "normative percent" refers to a "calculated," theoretical mineralogy, starting with the bulk composition of the rock, and commonly expressed in weight or volume percent.)

Anorthositic rocks are abundant in the ancient, heavily cratered highlands. Anorthosites are composed mainly of plagioclase feldspar. However, in addition to plagioclase, other highland rocks contain varying amounts of orthopyroxene, clinopyroxene, and olivine; norite is composed of unequal amounts of plagioclase and orthopyroxene, gabbro contains plagioclase and clinopyroxene, while troctolite is made up of plagioclase and olivine. Compositions of these highland rocks are shown in Fig. 3.

Breccias are present at all sample sites, but are particularly abundant at those sites with a large highland component (e.g., Apollo 14, 16, and Luna 20), as well as at Apollo 15 and 17. After much turmoil associated with many schemes of complex nomenclature for brecciated lunar rocks, the working classification of *Stöffler* (1980) has been generally accepted. Breccias are complex rocks and consist of fragments of rock, mineral, and meteorite fragments welded together by a fine-grained matrix. The amount of glass in the matrix depends upon the degree to which a given rock has been shocked during meteorite impact. Breccias range from poorly indurated aggregates of debris, all the way to complete impact-melt rocks. These melt rocks texturally resemble igneous rocks, but generally have compositions either similar to the soil or intermediate to the compositions of the soil and the lunar, plutonic, "pristine" rocks. It is not always easy to identify some of these rocks as melt products. The least ambiguous means for identifying "pristine" rocks is by analysis of siderophile elements (Ir and Au). Most meteorites have high siderophile contents, and melt rocks formed by impacting meteorites retain a signature of the impactor in the form of these siderophile elements.

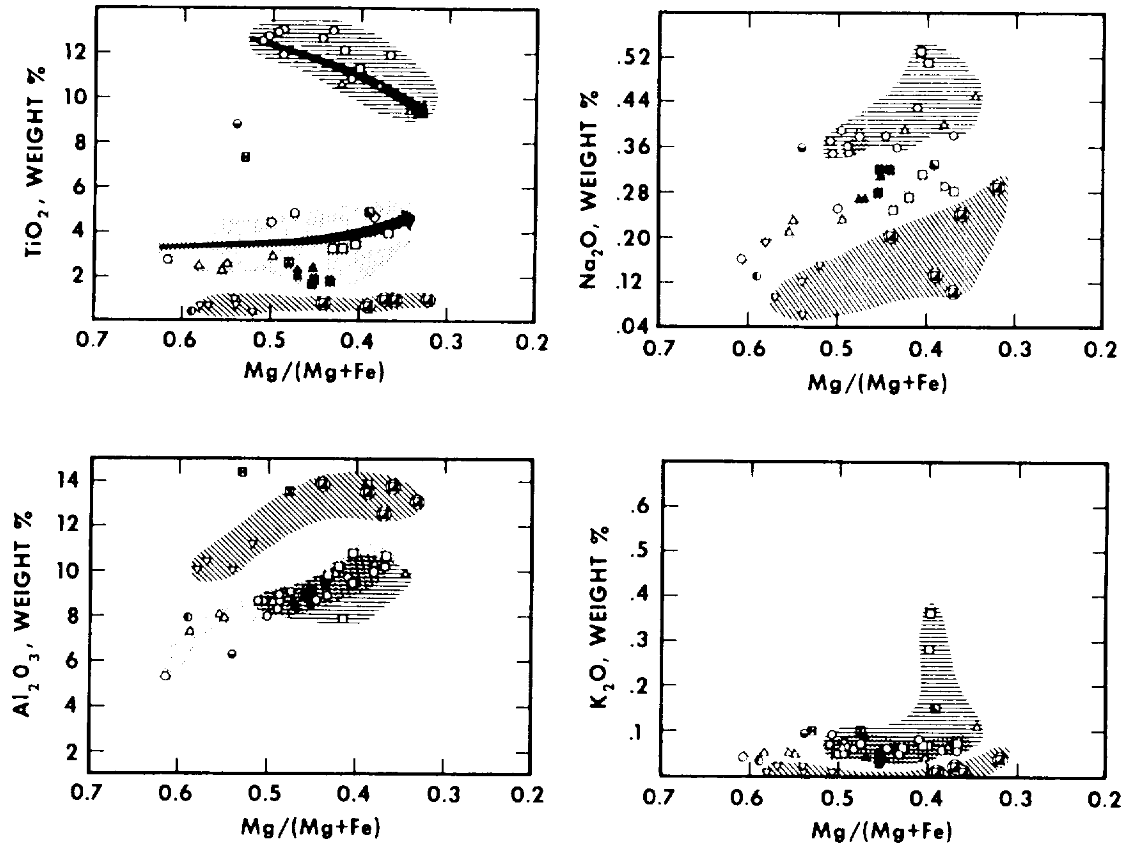


Fig. 2. Oxide variations vs. Mg′ for mare basalts (adapted from *BVSP*, 1981). Horizontal line shadings are for high-Ti basalts; dot shadings are for low-Ti basalts; diagonal line shadings are for very low-Ti (VLT) basalts.

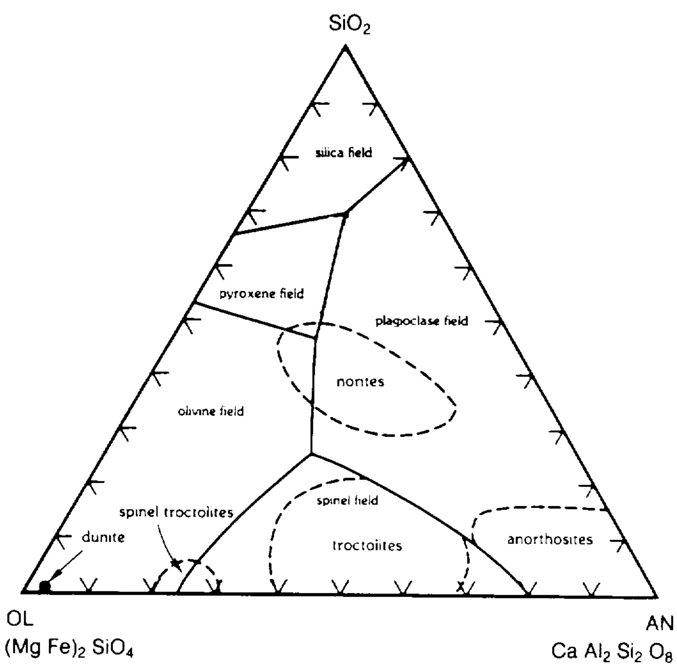


Fig. 3. Compositional fields of lunar highland igneous rocks plotted on the olivine (OL)-anorthosite (AN)-silica (SiO_2) pseudoternary diagram (adapted from *Taylor*, 1982).

SILICATE MINERALS

Most of the minerals that comprise the lunar rocks are silicates and are essentially the same as those commonly found in mafic, igneous rocks on Earth, i.e., olivine, pyroxene, and plagioclase. It is the nonsilicate phases, most of which are "opaque" to transmitted light when viewed in thin section, that are most distinctive of the lunar rocks. The abundances of the minerals in mare basalts are depicted in Fig. 4. As mentioned above, the highland igneous rocks consist mostly of plagioclase, with lesser amounts of pyroxene and olivine. The chemistry of these three rock-forming silicate minerals is presented below.

Pyroxene

Pyroxene is the general name for a group of minerals that displays considerable solid solution (i.e., range in chemistry). The compositions of pyroxenes in terms of the major elements (i.e., Ca, Fe, Mg) are commonly represented by use of the "Pyroxene Quadrilateral" where the corners are diopside ($CaMgSi_2O_6$), hedenbergite ($CaFeSi_2O_6$), ferrosilite ($Fe_2Si_2O_6$), and enstatite ($Mg_2Si_2O_6$), as shown in Fig. 5. Pyroxenes with compositions near or on the enstatite-ferrosilite join have orthorhombic crystal symmetry and are termed "orthopyroxenes," whereas all other compositions represent pyroxenes with monoclinic symmetry and are termed "clinopyroxenes." Pyroxenes with 4-7% CaO are

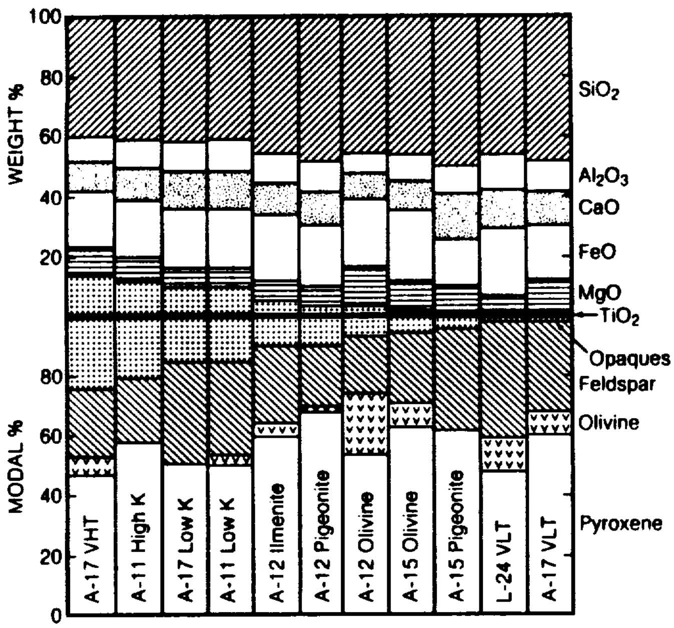


Fig. 4. Mare basalt major-element chemistry and modal mineralogy, ordered from left to right by decreasing TiO_2 (or opaque oxide) content (adapted from *BVSP,* 1981).

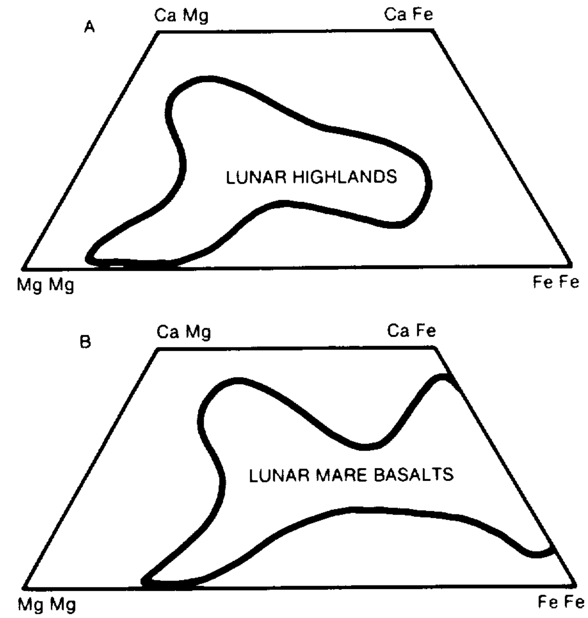


Fig. 5. Lunar pyroxene major-element chemistry plotted on the "pyroxene quadrilateral." The corners clockwise from the upper left are diopside ($CaMgSi_2O_6$), hedenbergite ($CaFeSi_2O_6$), ferrosilite ($Fe_2Si_2O_6$), enstatite ($Mg_2Si_2O_6$).

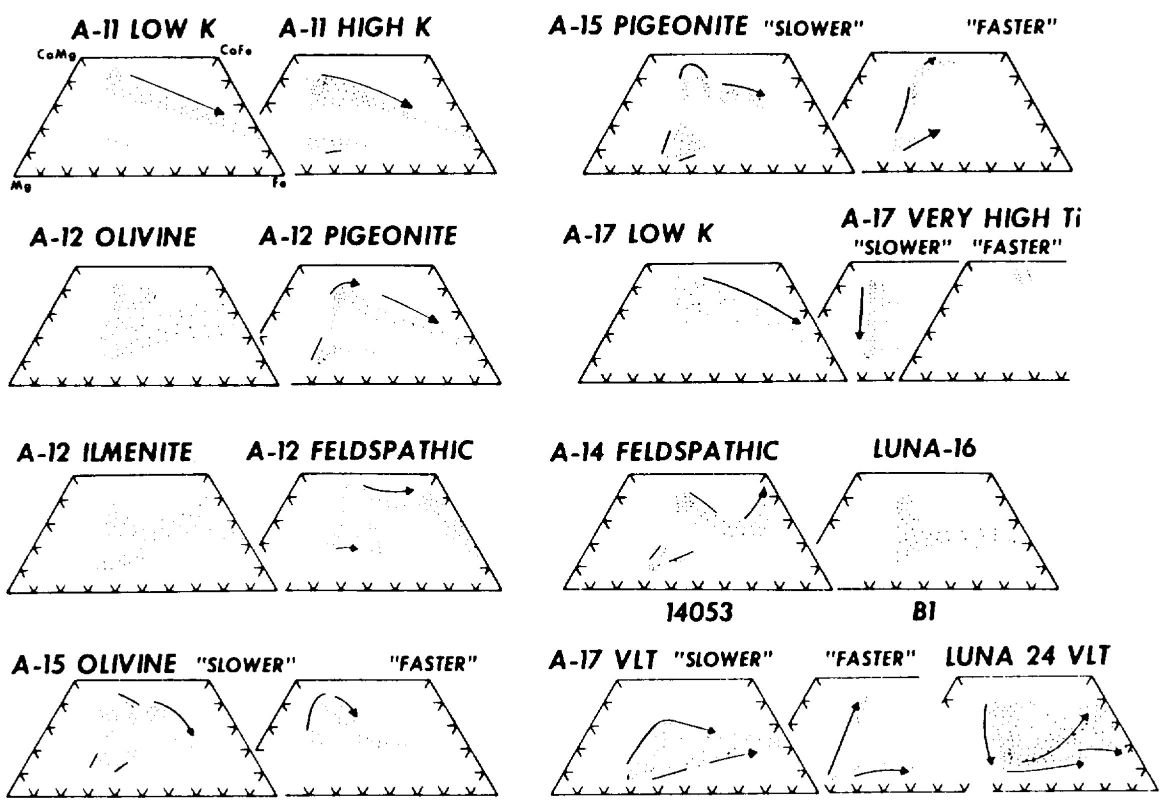


Fig. 6. Mare basalt pyroxene variations with arrows indicating important crystallization trends (adapted from *BVSP,* 1981).

called "pigeonites," those with 12-16% CaO are "subcalcic augites," and those with >16% CaO are augites. Pyroxferroite is a mineral that was first discovered in lunar samples and has a composition near the Fe-rich end of the hedenbergite-ferrosilite join. The minor elements in lunar pyroxenes include Al, Ti, Cr, and trace amounts of Na. Their use as discriminant parameters can usually be more effective for basalt petrogenesis than the major-element chemistry.

As shown in Fig. 5, the pyroxenes in the highland rocks do not range in composition to the high FeO contents so characteristic of the mare basalts. This is largely a result of (1) the higher MgO contents [usually expressed as Mg/(Mg+Fe) ratios] of the highland rocks and (2) the slower cooling rates that aid the attainment of equilibrium, thereby restricting chemical variation. The more extensive chemical zonation of the pyroxenes in mare basalts is commonly represented by their overall Fe enrichment and Ca depletion, frequently resulting in pyroxferroite. This zonation can be observed in the basalts, sometimes within a single grain, as orthopyroxene cores mantled by pigeonite, in turn mantled by augite, commonly grading to ferropyroxenes, as shown in Fig. 6. The chemical trends in the pyroxenes are not only a result of the melt composition, but more importantly, the cooling rates (and associated kinetics) of the crystal-melt system. These effects are particularly well displayed by the Apollo 15 basalts (Fig. 6).

Olivine

Olivine is a silicate material that displays a solid solution series (range in chemical composition without phase change) between Mg_2SiO_4 (forsterite, abbreviated as Fo) and Fe_2SiO_4 (fayalite, abbreviated as Fa). Compositions are given in terms of mole percent of Fo or Fa. All other elements are present in amounts <1 wt%. The most abundant of these minor elements in olivine are Mn, Ni, Ca, Cr, Co, and Al.

Olivine is a major mineral in many basalts where it may constitute 0-35% by volume of the rocks. As shown in Fig. 7, it has compositions ranging from 20% to 70% Fa (Fo 80 to Fo 30), with some near-pure fayalite in the late-stage mesostatis (final residue from crystallization) of the basalts. Olivine in basalts is always zoned from Mg-rich cores to more Fe-rich rims, e.g., from Fo 80 to Fo 30 (Fa 20 to Fa 70). This Fe-enrichment in olivine is similar to that observed in the pyroxenes, where continued crystallization of these phases results in Mg-depletion with subsequent Fe-enrichment in the melt. Olivine constitutes from 0% to 100% of highland rocks, where it has compositions from Fa 7 to Fa 18 (Fo 93 to Fo 82). Olivine is less than 10% by volume in anorthosite, 10-20% in troctolite, 0-15% in gabbronorite, and up to 100% in dunite.

Plagioclase Feldspar

The majority of lunar feldspars are calcic plagioclases ($CaAl_2Si_2O_8$; anorthite, abbreviated as An) in solid solution with sodic plagioclase ($NaAlSi_3O_8$; albite, abbreviated as Ab). Lunar plagioclase also contains trace amounts of K-feldspar ($KAlSi_3O_8$; orthoclase, abbreviated as Or) in solid solution. The compositions of feldspars are commonly given as mole percent of these three components, An, Ab, Or. As shown in Fig. 8, the compositions of plagioclase in mare basalts range from An 98 to An 74. The Or contents are minor (0-3%). Rare K- and Ba-feldspars are present in late-stage mesostasis in some of the mare basalts, particularly those rich in KREEP components. The compositions of feldspars in highland rocks commonly contain even fewer alkalis, e.g., An 99 to An 90, Or 0 to 2. The low Ab and Or contents of lunar plagioclase are a consequence of the low alkali contents of the magmas that formed the lunar rocks.

Plagioclase commonly displays chemical zonation, with calcic cores grading outward to more Na- and K-rich compositions. In addition, Fe content of plagioclase, particularly in mare basalts, can range from as much as 0.5% in the cores to over 1% in the rims. Furthermore, the Fe content of mare basalt plagioclase is considerably higher than those of highland feldspars. Thus, based solely on the Fe content of the plagioclase, the mare vs. highland origin of a single particle can be determined.

The trace-element chemistry of lunar plagioclase is important for lunar evolutionary models. Plagioclase frequently contains relatively more Eu than other rare earth elements (REE). This

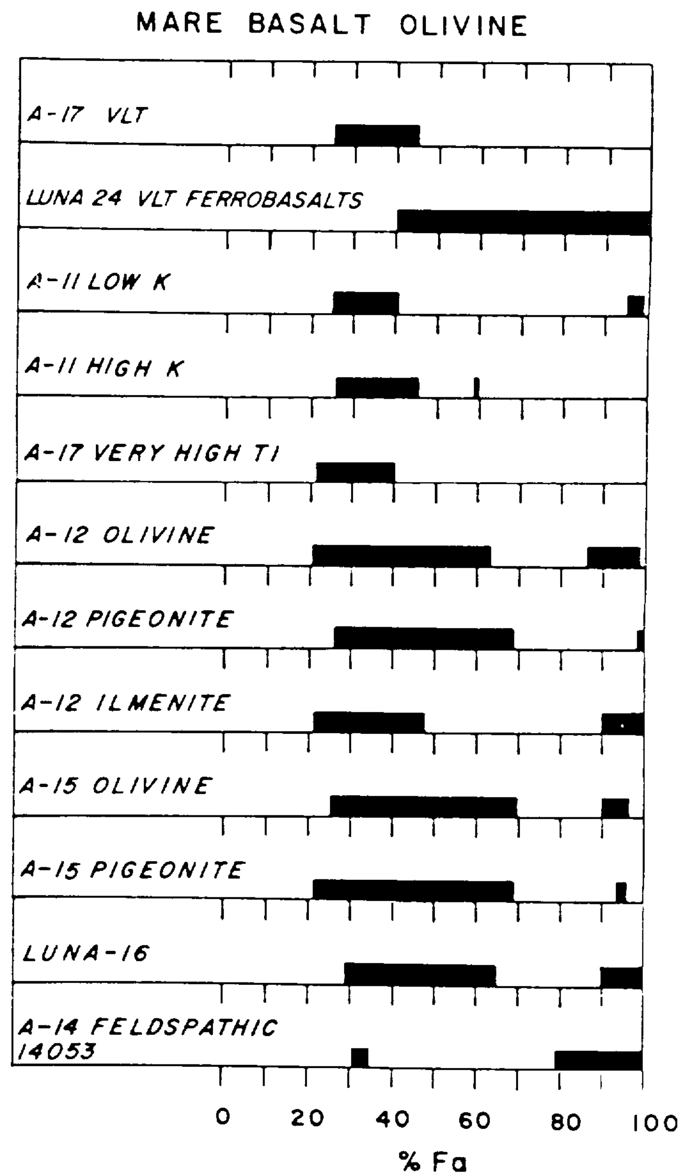


Fig. 7. Fayalite content along the join Fe_2SiO_4-Mg_2SiO_4 for mare basalts (adapted from *Papike and Vaniman*, 1978).

positive Eu anomaly, caused by the dual valance of Eu (2+, 3+) compared with the other REE, indicates that there are other minerals that must have negative Eu anomalies. The plagioclase in the anorthosites of the lunar highlands contains positive Eu anomalies. This led to the "magma ocean theory," which postulates that during the first 100 m.y. after the formation of the Moon, the outer portions melted to depths of 100 km or so, and as this magma cooled, plagioclase crystallized and floated to the top of the melt to eventually aggregate into large masses forming the early lunar crust, now referred to as the highlands. The other, more Mg- and Fe-rich, minerals settled to the depths of the ocean forming the residual from which basalts were later generated. However, this lower portion had a negative Eu anomaly as, consequently, did the derivative basalts. From this brief narrative, it should be possible to realize that the recognition of these Eu anomalies is one of the important discoveries of lunar geochemistry, and that this signature has permitted major interpretations of lunar (and terrestrial) evolution.

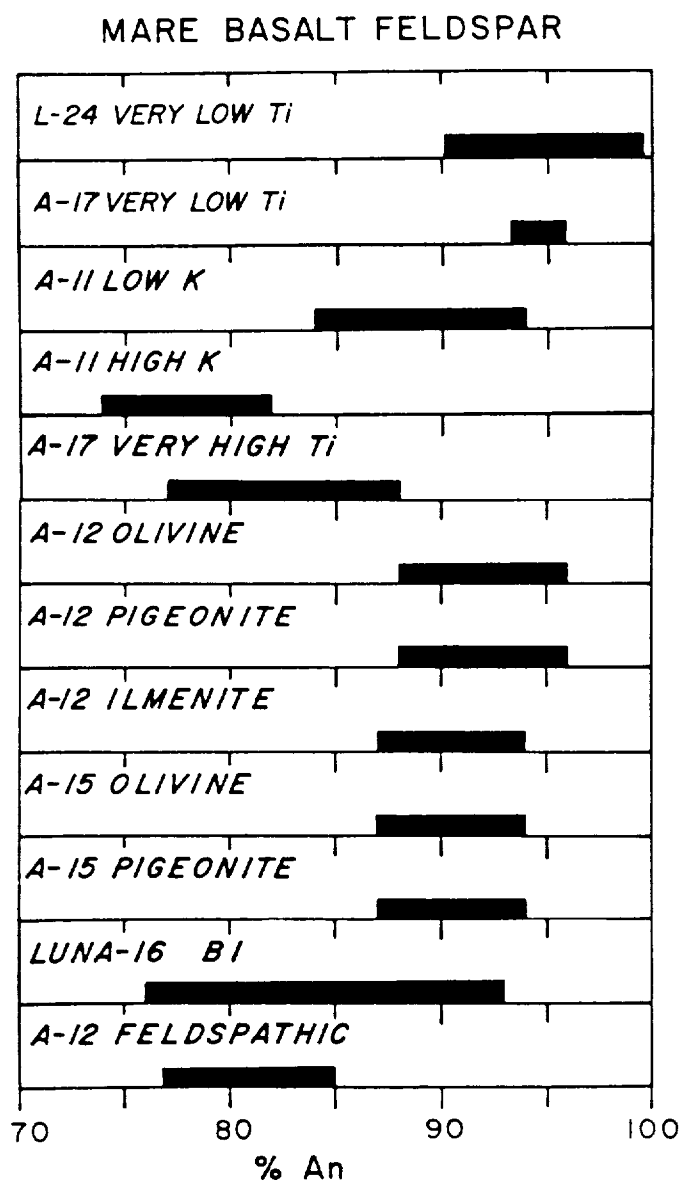


Fig. 8. Anorthite content ($CaAl_2Si_2O_8$) of mare basalt feldspars (adapted from *Papike and Vaniman,* 1978).

OXIDE MINERALS

The nonsilicate minerals, which are minor yet important constituents of lunar rocks, include ilmenite, spinels of various chemistry, armalcolite, rutile, baddeleyite, fluorapatite and chlorapatite, whitlockite, troilite and other sulfide phases, and native FeNi metal phases. Schreibersite, cohenite, and niningerite, minerals largely of meteoritic origin, are present only in trace amounts. The first several minerals in this list, namely the oxides, are the most important phases in lunar rocks and soils.

The oxide minerals in lunar rocks are signatures of the conditions of formation (e.g., fO_2) of the rocks in which they occur. They also have tremendous potential for utilization with any future lunar base activities. Whereas lunar silicate minerals are basically the same as those of Earth, the oxide phases, most of which are "opaque" minerals, reflect the reducing conditions on the Moon that prevailed during their formation.

Ilmenite

Ilmenite is the most abundant opaque mineral in lunar rocks. It has hexagonal symmetry and compositions near $FeTiO_3$. Most lunar ilmenite contains some Mg, the result of the solid solution which exists between $FeTiO_3$ (ilmenite) and $MgTiO_3$ (the mineral geikielite). All other elements, including Cr, Mn, V, and Zr, are <1%. Although terrestrial ilmenite almost always contains some Fe^{3+}, lunar ilmenite contains none, a reflection of the general reducing state of the magmatic conditions on the Moon. The amount of ilmenite in a rock is largely a function of the bulk composition of the magma from which the ilmenite has crystallized. Effectively, the higher the TiO_2 content of the rock, the higher the ilmenite content. Indeed, ilmenite contents of 15-20% are common for Apollo 11 and 17 basalts.

The compositions of lunar ilmenite vary and plot along the $FeTiO_3$-$MgTiO_3$ join (Fig. 9). The high magnesium contents of many ilmenites are similar to terrestrial ilmenites from kimberlites, which are of high-pressure formation. It was originally thought that the Mg content of lunar ilmenites was also a reflection of high pressure of formation; however, the lunar ilmenites with the highest Mg contents are from Apollo 17 mare volcanic rocks. Instead, the composition correlates with the bulk composition of rock, a reflection of the primary magma. Indeed, the distribution of Mg between ilmenite and silicates is related to the position of ilmenite within the crystallization sequence, which itself is a function of cooling rate and oxygen partial pressure (i.e., fO_2). However, it is doubtful that these MgO contents all represent equilibrium conditions, since the composition of ilmenite can vary significantly even within one rock (Fig. 10).

The stability curve of pure ilmenite is below that for ulvöspinel, the spinel phase with which it is commonly associated (Fig. 11). In fact, ilmenite is commonly formed as a product of subsolidus reduction of this high-Ti spinel (discussion below).

The production of oxygen on the Moon from lunar materials is important in establishing a lunar base. Ilmenite can be reduced to rutile plus iron with the release of oxygen (*Williams et al.,*

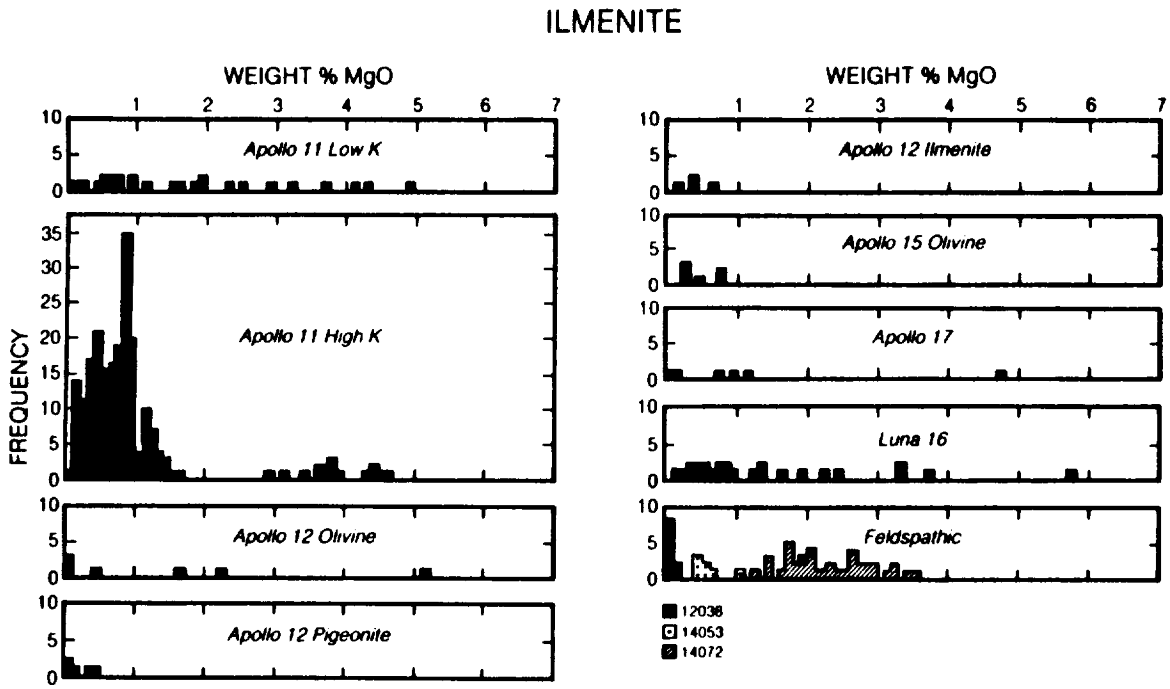


Fig. 9. MgO (wt%) content for various mare basalt ilmenites (adapted from *Papike et al.*, 1976).

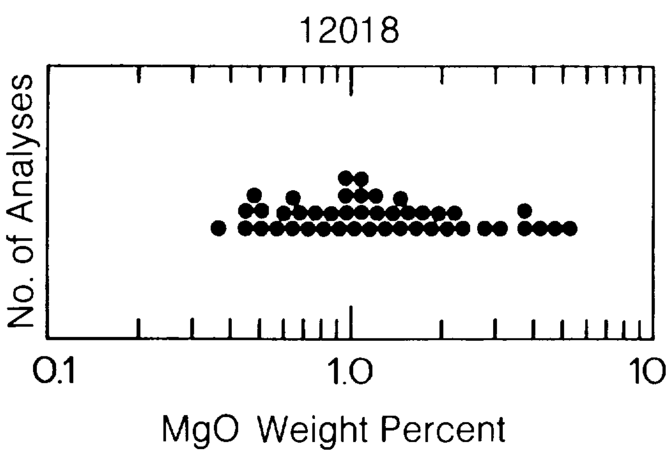


Fig. 10. MgO (wt%) variations in ilmenite from one rock (adapted from *El Goresy et al.*, 1971).

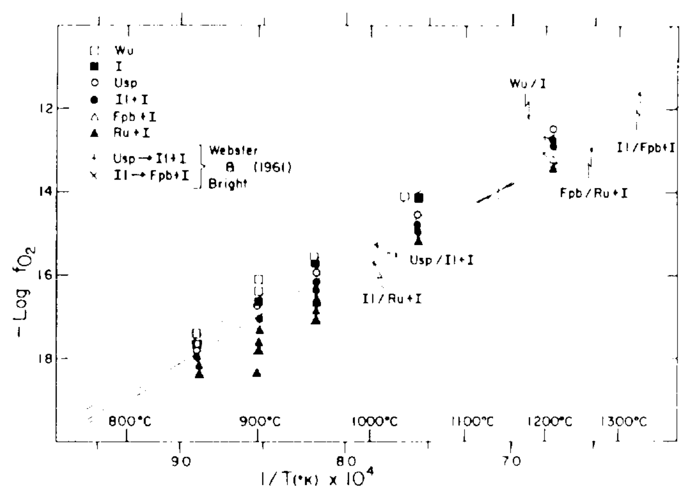


Fig. 11. Fugacity of oxygen vs. temperature plot of the univariant curves in the Fe-Ti-O system (adapted from *Taylor et al.*, 1972). Abbrev.: Wu = wüstite; I = iron; Usp = ulvöspinel; Il = ilmenite; Fpb = ferropseudobrookite; Ru = rutile.

1979). This reaction is that associated with the lower univariant curve on Fig. 11, determined by *Taylor et al.* (1972)

$$FeTiO_3 = TiO_2 + Fe + 1/2O_2$$

$$10.5\ \text{wt\%}\ O_2 \qquad (1)$$

The amount of oxygen produced by this reduction reaction is large. This reaction could be accomplished by the hydrogenation of ilmenite using indigenous solar-wind-implanted protons (hydrogen), adsorbed and abundant on grains of the lunar soil. Preliminary studies have shown that oxygen production by this method is feasible (*Williams*, 1985; *Gibson and Knudsen*, 1985). These preliminary studies have been conducted largely with terrestrial ilmenite, which contains varying amounts of Fe^{3+}. The complications associated with the Fe^{3+}-free, high-MgO lunar ilmenite, particularly from Apollo 17, remain to be evaluated. Indeed, even the beneficiation of an ilmenite feedstock from lunar soil may not be a simple, one-step process (*Taylor and Oder*, 1990).

Another possible source of oxygen is the spinel phase, ulvöspinel (Fe_2TiO_4), according to the reaction

$$Fe_2TiO_4 = TiO_2 + 2Fe + O_2 \qquad (2)$$

$$14.3 \text{ wt\% } O_2$$

The O_2 yield from the reduction of ulvöspinel is greater than for the ilmenite reaction. However, even though this spinel phase is present up to several percent in basalts from Apollo 12, 15, and 17, its composition is quite variable compared with ilmenite (see "Spinel Group" section below), and ilmenite is generally more abundant. The compositional variability could introduce complications into its large-scale use for lunar oxygen production.

Spinel Group

Spinel is the name for a group of minerals with cubic symmetry that display extensive solid solution. The general structural formula for these minerals is $A^{iv}B_2^{vi}O_4$, where A typically represents 2+ cations in tetrahedral (iv) coordination (e.g., Fe^{2+}, Mg^{2+}) and B represents 3+ or 4+ cations in octahedral (vi) coordination (e.g., Cr^{3+}, Al^{3+}, Ti^{4+}). The various members of the spinel group of minerals (Fig. 12) include chromite ($FeCr_2O_4$), ulvöspinel ($FeFeTiO_4$, commonly written as Fe_2TiO_4; Fe^{2+} is in both iv and vi coordination), hercynite ($FeAl_2O_4$),and spinel (*sensu stricta*) ($MgAl_2O_4$). Solid solution compositions between these end members are designated by the use of modifiers such as "chromian" ulvöspinel or "titanium" chromite. Some solid solution compositions have distinct names, such as pleonaste for compositions essentially between $MgAl_2O_4$ and $FeAl_2O_4$ (Fig. 12).

In lunar basalts, spinels have complicated and varied chemistry. As shown in Fig. 13, besides the major oxides FeO, Cr_2O_3, and TiO_2, chromites have higher contents of Al_2O_3, MgO, and V_2O_3 than ulvöspinels, with V_2O_3 contents near 1%. In typical mare basalts, chromite is one of the first phases to crystallize, as evidenced by its inclusion in Fo-rich olivine. If the chromite is completely included within the olivine, it is effectively isolated from the melt and undergoes no further growth or chemical change. However, if the chromite is in contact with the melt, it will continue to grow, increasing in TiO_2 and FeO and decreasing in Al_2O_3, MgO, and Cr_2O_3, the overall composition moving toward ulvöspinel (Fig. 14). Most of the basalts that contain both titanian chromites and chromian ulvöspinels possess the latter phase as overgrowths on the chromite. In reflected light, the ulvöspinel appears as brown to tan rims about the bluish chromite. The contact between the two is commonly sharp and is reflected in a discontinuity in the compositional trend from core to rim. This break probably reflects a cessation in crystallization, followed later by renewed growth in that the earlier chromite grains acted as the nuclei. Some rocks (e.g., 12018, Fig. 13) contain spinel grains that display diffuse contacts, also reflected in gradational changes in the chemistry of the solid solution. This could result from continuous crystallization of spinel or subsolidus reequilibration involving solid-state diffusion.

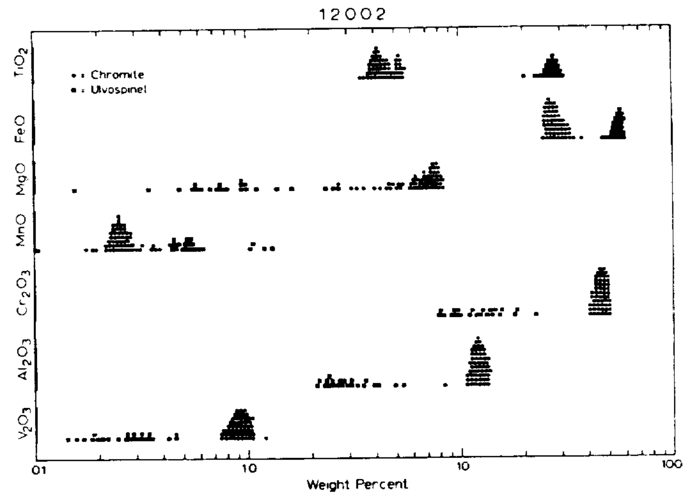


Fig. 13. Elemental distribution diagrams for chromites and ulvöspinels in typical Apollo 12 basalt (adapted from *El Goresy et al.,* 1971).

The spinel compositions of lunar rocks are typically represented within the ternary system: $FeCr_2O_4$-Fe_2TiO_4-$FeAl_2O_4$. The addition of Mg as another major component (actually, $MgAl_2O_4$) provides a third dimension to this system (Figs. 12 and 14). The principal cation substitutions of the solid solution in these lunar phases can be represented by $Fe^{2+} + Ti^{4+} = 2(Cr,Al)^{3+}$. The generalized compositional trends of the spinels in lunar mare basalts are shown in Fig. 14. Spinels are ubiquitous in mare basalts where they display various textures and associations. They are second in abundance only to ilmenite as the opaque mineral in basalts. They make up to 10-12% of some basalts (e.g., those from Apollo 12).

Spinels also occur in nonmare rocks such as anorthosites, anorthositic gabbros, and troctolites, although in much lower abundance than in mare basalts. The spinels in the anorthositic rocks tend to be chromites with lesser amounts of MgO, Al_2O_3, and TiO_2 than those in basalts. Certain highland rocks, notably troctolites, contain a spinel phase called pleonaste (slightly Fe- and Cr-rich of the midpoint along the $MgAl_2O_4$-$FeAl_2O_4$ join, Figs. 12 and 14). This spinel is not opaque, but it stands out in thin section because of its pink color, high refraction index, and isotropism.

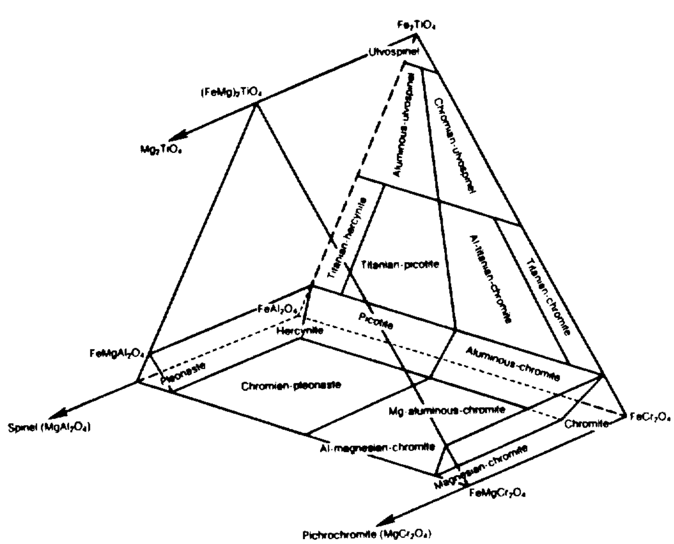


Fig. 12. Nomenclature for lunar spinels (adapted from *Haggerty,* 1972).

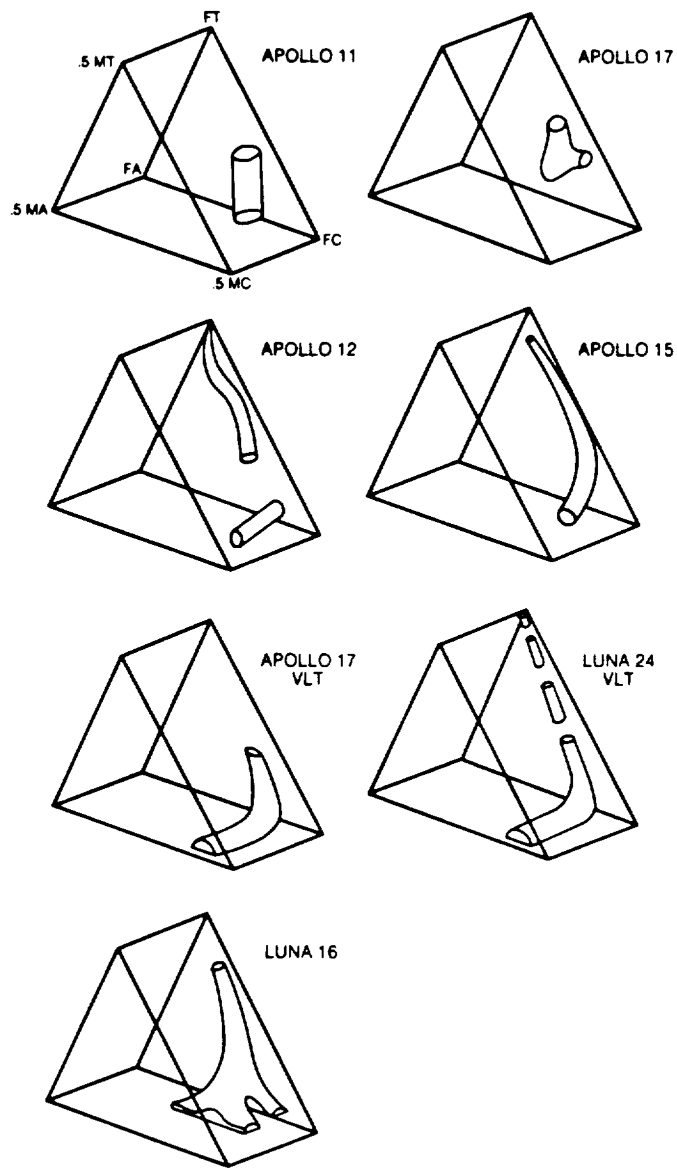


Fig. 14. Perspective views of the 3-D system $FeCr_2O_4$-Fe_2TiO_4-$FeAl_2O_4$-$MgAl_2O_4$ for mare basalt spinel compositions (modified from *Haggerty*, 1972).

Normal processes accompanying and subsequent to crystallization in terrestrial rocks involve oxidation; however, in lunar rocks and soil, the normal situation involves reduction. Ulvöspinel grains are often reduced to ilmenite + native Fe and sometimes to rutile + native Fe. This is the normal paragenetic sequence with lunar rocks and involves these subsolidus reactions (Fig. 15). In a few rocks (e.g., 14053, 14072), the Ti-rich spinel, ulvöspinel, is reduced to a Ti-poor spinel, titanian chromite, ilmenite, and native Fe. Figure 15 addresses this type of reaction. During normal crystallization of spinel from a melt, the spinel typically begins as chromite and changes its composition toward ulvöspinel as growth continues. The effect of the later subsolidus reduction on the last-formed ulvöspinel is to "exsolve" ilmenite + native Fe with the residual components enriching the remaining spinel, such that its composition moves toward chromite. As well as being evidence for reduction of spinel, this secondary generation of the native Fe is important as a lunar base raw material. In fact, spinel in the soil readily undergoes reduction when shock metamorphosed by impacting micrometeorites. This reduction is driven by the presence of solar-wind-implanted particles, notably the elements hydrogen and carbon, which impart a reducing environment when heated to the high temperatures caused by the impacts.

Armalcolite

Armalcolite was first recognized as a mineral in samples from the Apollo 11 site where it occurs as an accessory mineral in Ti-rich basalts. Although its composition is strictly defined as $(Fe_{0.5}Mg_{0.5})Ti_2O_5$, the name is also used in a broader sense to describe the intermediate portions of the solid solution series $FeTi_2O_5$-$MgTi_2O_5$ (Fig. 16). Detailed chemical analyses of

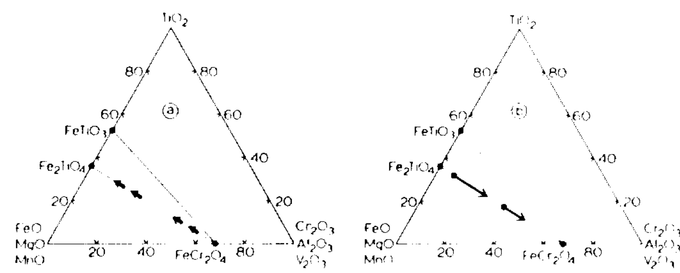


Fig. 15. Spinel compositional variations during **(a)** crystallization from a silicate melt and **(b)** subsolidus reduction (adapted from *El Goresey et al.*, 1972).

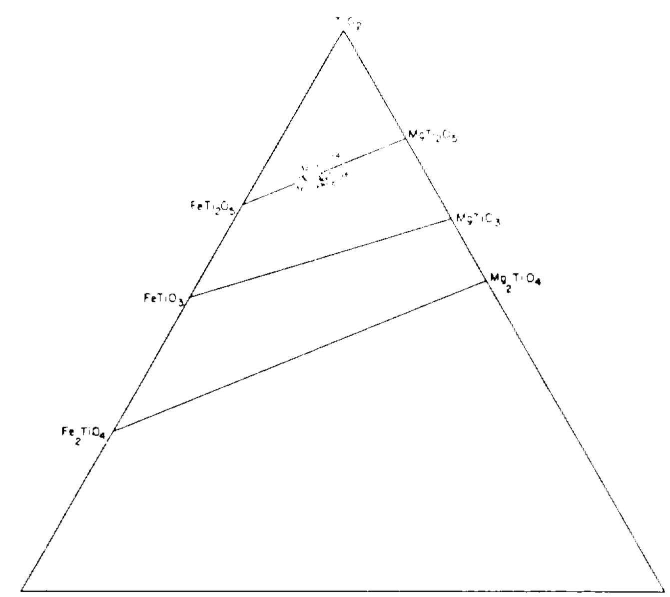


Fig. 16. Armalcolite compositions (wt%) plotted in the system FeO-MgO-TiO_2 (adapted from *Anderson et al.*, 1970).

armalcolite, with crystal-chemical considerations of charge balance within the structure, have shown the presence of appreciable amounts of Ti^{3+} (Fig. 17). This is another result of the distinctly reducing environment that prevailed during the formation of lunar igneous rocks. This presence of Ti^{3+} in lunar armalcolite is noteworthy since it sets off the lunar varieties from armalcolites subsequently found on Earth.

The occurrence of armalcolite is restricted to high-TiO_2-content rocks that have cooled relatively rapidly; slow cooling results in the reaction of early-formed armalcolite and liquid to form magnesian ilmenite. In practice, there are three distinct compositional types or varieties of armalcolite in lunar samples (Fig. 18). The first and most abundant type (>95% of observed) is represented by compositions intermediate to the solid solution series described above. This is the typical occurrence in Apollo 11 and 17 basalts, although it is found in samples returned from all missions. Two varieties of this first type have been characterized as gray and tan in color. These have overlapping compositions but appear to be present in different petrographies, with the most common type being the gray variety, which has rims of high-Mg ilmenite. Although it was suggested that these varieties were polymorphs, the crystal structures have been determined to be identical. Because the compositions are not distinctly different either, these are simply varieties, not polymorphs of armalcolite.

The second compositional type of armalcolite is characterized by having high ZrO_2 (3.8-6.2 wt%), Cr_2O_3 (4.3-11.5 wt%), and CaO (3.0-3.5 wt%) contents. This type is called Cr-Zr-Ca-armalcolite. The third type has a composition between the first, Fe-Mg titanate, and the second, Cr-Zr-Ca titanate. This armalcolite is termed Zr-armalcolite and has definitive amounts of ZrO_2 (2.0-4.4 wt%), Y_2O_3 (0.15-0.53 wt%), and Nb_2O_5 (0.26-0.65 wt%). These last two types of armalcolite are potentially important as resources of ZrO_2.

Other Oxide Minerals

The only other oxide minerals of any volumetric significance in lunar rocks and soils are rutile (TiO_2) and baddeleyite (ZrO_2). Rutile is generally associated with ilmenite and most commonly occurs as a reaction product from the reduction of ilmenite and/or armalcolite. In such cases, this rutile is secondary, forming after the initial formation of the rock. Primary rutile is rare and occurs as discrete, euhedral grains, typically associated with ilmenite. This rutile often contains Nb, Cr, Ta, and REE. Baddeleyite commonly occurs in "melt rocks," which are formed by large meteorite impacts that effectively melt the soil into a silicate magma that subsequently recrystallizes into an igneous rock, not much different from the other normal igneous rocks. However, it does have various amounts of meteoritic constituents. An example is Apollo 14 rock 14310, which contains abundant baddeleyite and schreibersite [$(Fe,Ni)_3P$], both, most likely, residual from meteorites. Where baddeleyite occurs, the ilmenite commonly contains appreciable zirconium (i.e., up to 0.6% ZrO_2), and the Zr-bearing forms of armalcolite may also be present.

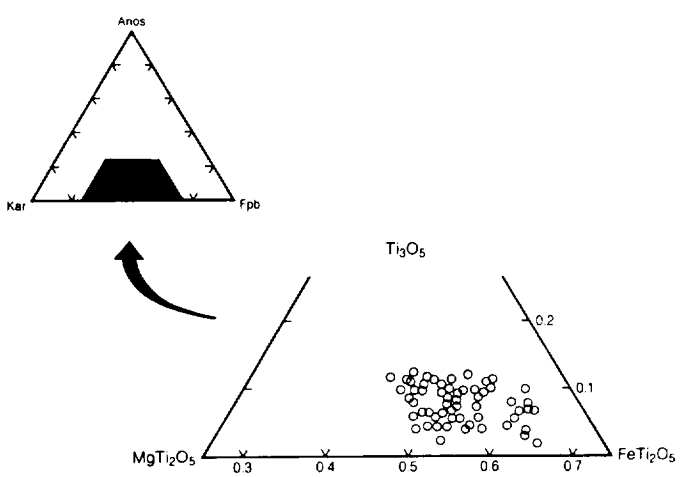


Fig. 17. Armalcolite compositions from mare basalts depicting the amount of Ti^{3+} as anosovite (Ti_3O_5) as calculated from electron microprobe analyses (adapted from *Papike et al.,* 1976).

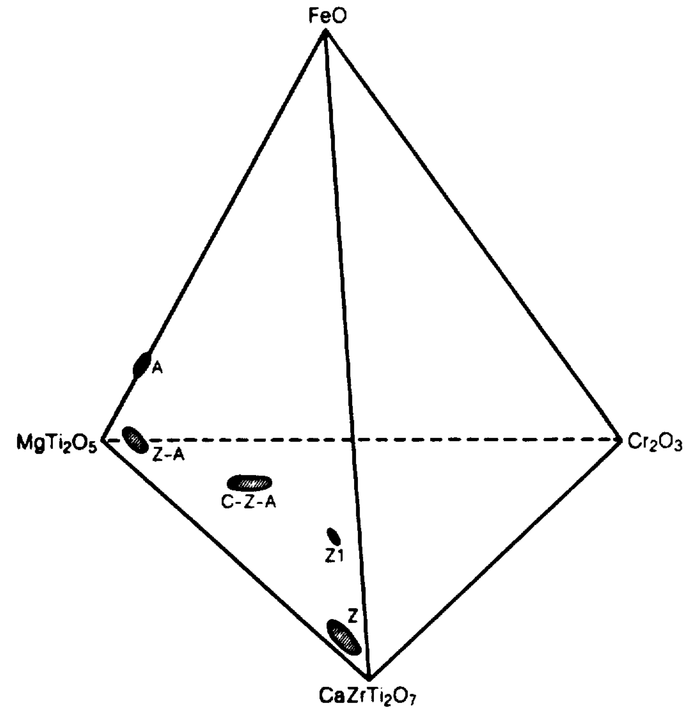


Fig. 18. Compositions (wt%) for armalcolite (A), Zr-armalcolite (Z-A), Cr-Zr-Ca-armalcolite (C-Z-A), Phase Z1, and zirconolite (Z) (adapted from *Haggerty,* 1973).

SULFIDE MINERALS

Troilite is the most common of the sulfide minerals in lunar rocks. It is ubiquitous and commonly associated with native Fe and/or ilmenite and/or spinel. It was originally thought that the troilite was always associated with native Fe in a texture reminiscent of the 988°C eutectic between Fe and FeS. This is undoubtedly one of the origins of troilite in the lunar rocks; however, there are several others. In all occurrences, the amount of troilite is usually less than 1% by volume.

The most common occurrence of troilite is as an accessory phase in mare basalts, where it is usually a late-stage crystallization product. It is commonly associated with ilmenite and spinel, but also with native Fe. Its formation is a result of the bulk

composition of the melt, in particular, the S content. The volatility of S controls the formation of secondary troilite during meteorite-induced shock metamorphism. Some of the Apollo 16 rocks, notably 66095, "Rusty Rock," contain troilite that most likely formed as a direct result of the remobilization of sulfur during the impact process. The chemistry of troilite is essentially that of FeS with <1 wt% of all other components.

Other sulfides that have been positively identified include chalcopyrite, cubanite, and sphalerite. These phases have only been found as small (<10-15 μm) grains in some Apollo 12 basalts. Sphalerite was observed in some Apollo 16 breccias where it was probably formed as a result of mobilization of Zn and S during shock metamorphism. It is only present as small (<20 μm) grains and in minor quantities (<0.01 vol%).

NATIVE IRON

Iron present as Fe^0 is not common in terrestrial rocks; however, in lunar rocks, it is an extremely common phase largely because of the low oxygen fugacities prevailing at the time of magma crystallization (Fig. 1). Native Fe is present as two phases in various proportions that are usually intergrown, kamacite (0-8% Ni) and taenite (8-50% Ni). Native Fe occurs in lunar samples as (1) indigenous, normal igneous metal, (2) Fe formed by reduction of certain minerals (e.g., ulvöspinel), (3) fragments of meteoritic metal, and (4) metal crystallized from lunar soil impact metamorphism formed during the normal crystallization of lunar highland and mare igneous rocks. In practice, it is the native Fe in the lunar soil that is the most common and easiest to recover.

Figure 19 shows a plot of Co vs. Ni contents for native Fe metal. The diagonal lines outline the "meteoritic field" that *Goldstein and Yakowitz* (1971) mistakenly designated as unique to metal from meteorites. The composition of metal within this field does not imply that it is of meteoritic origin. It may be indigenous lunar. Here, these boundary lines are used simply for reference.

The Ni and Co contents of native Fe metal can vary considerably, from 0% to over 50% Ni and from 0% to 4% Co. Figure 20 shows the chemical variation of native Fe for several Apollo 16 highland samples. Of all lunar samples, it is reasonable to suppose that the highland rocks contain the most meteoritic metal. In practice, the contents of certain siderophile elements in the soil, notably Ir, W, Re, Au, etc., are meteoritic signatures that have been used to estimate the influx of this type of extralunar matter. Using such signatures, the amount of meteoritic material in the highland soils has been estimated to be only 1-3%.

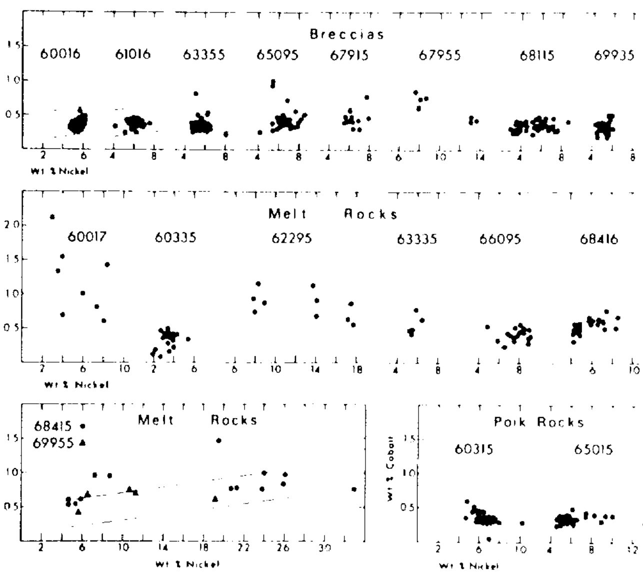


Fig. 20. Nickel and Co contents (wt%) of native Fe grains in numerous Apollo 16 rocks (adapted from *Misra and Taylor*, 1975). The diagonal parallel lines are used for reference (see Fig. 19 caption).

With the return of the first lunar samples, it was noticed that the ferromagnetic resonance (FMR) signal from the lunar soil samples was greater than that from rock samples. Therefore, there must be considerably more metallic Fe (i.e., Fe^0) in the soils than in the rocks. Since the soils were composed of disaggregated rock material, this pointed to something unique occurring during the process of soil formation. Indeed, unraveling the origin of this additional native Fe in the soils led to our understanding of the complicated processes inherent in lunar soil formation (discussed below).

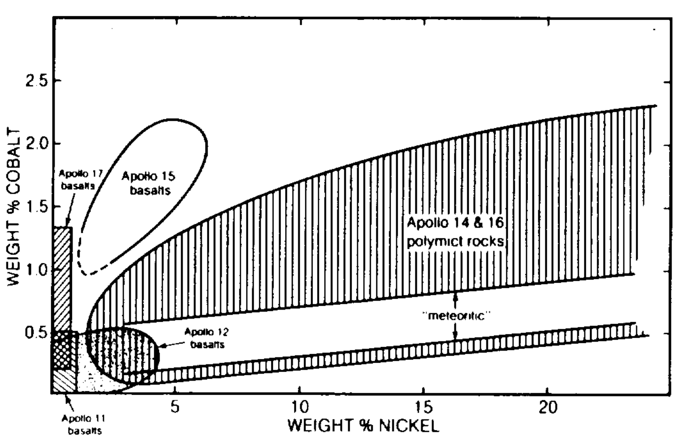


Fig. 19. Native Fe metal compositions by mission as compiled from the literature. The region labeled "meteoritic" is not necessarily indicative of metal originating from a meteorite, but is used for reference (see *Misra and Taylor*, 1975).

LUNAR SOIL FORMATION AND THE ORIGIN OF SINGLE-DOMAIN NATIVE IRON

As mentioned above, the lunar soil contains several times more native Fe than the rocks from which the soil was derived. This apparent paradox has given us important clues toward understanding lunar soil formation. The following discussion on the origin and significance of this free Fe in the lunar soils is taken largely from *Taylor and Cirlin* (1986).

What is inherently different between the lunar rocks and soils? Without the shielding atmosphere that the Earth possesses, meteoritic particles impinge upon the lunar surface with velocities on the order of 40,000-250,000 km/hr, thereby causing considerable damage, with craters ranging in size from thousands of kilometers to <1 μm. The size of the particles that produced these smallest of craters ("zap pits") is about 10% of the diameter of the crater. The flux of the small particles (i.e., micrometeorites)

was always greater than the flux of the large meteorites. The larger impacts smash large rock material into smaller pieces and move material great distances from its origin, but the soil development is largely a function of micrometeorite impacts.

Two basic processes form the lunar soil: (1) simple comminution, disaggregation or breaking of rocks and minerals into smaller particles and (2) agglutination, the welding of lithic and mineral fragments together by the glass produced by the quenching of micrometeorite-produced impact melt. These two processes compete to decrease and increase, respectively, the grain size of soil particles. Figure 21 depicts the comminution and agglutination of the lunar soil particles at a small scale. The glass-welded particles are called "agglutinates."

Ferromagnetic resonance studies of the rocks and soils detected a characteristic resonance that was only associated with agglutinates and regolith breccias (larger samples of impact-produced material). This characteristic resonance is produced by large numbers of "single-domain (SD) Fe^0," that is, metallic Fe in the size range of 40-300 Å. It seems that the abundant agglutinates, the presence of which in the lunar soil was not anticipated before Apollo, are the carriers of much of the single-domain Fe^0 in the soil. Transmission electron microscopic (TEM) studies of the glass in some of the agglutinates provided the first direct determination of the actual sizes of the numerous single-domain Fe^0 (Fig. 22). The majority of the grains are in the range of 100-200 Å, well within the single-domain size range. Subsequent FMR Curie point measurements showed that these particles are essentially pure elemental Fe in composition.

What is the origin of this abundant single-domain Fe^0? The soil on the Moon is continually bombarded with solar wind and has effectively become saturated with solar-wind-implanted elements, notably H and C. When a portion of the soil is melted by micrometeorite impact, these elements impose a very reducing environment such that Fe^{2+} in the silicate melt is effectively reduced to elemental Fe^0 that precipitates as myriad tiny Fe^0 spheres that are disseminated within the quenched melt (i.e., the glass). The melting and cooling process is so fast that it prevents the native Fe from diffusing and aggregating into larger sized particles. This "autoreduction process" is responsible for the production of the additional Fe^0 that resides in the agglutinates and distinguishes the soils from the rocks.

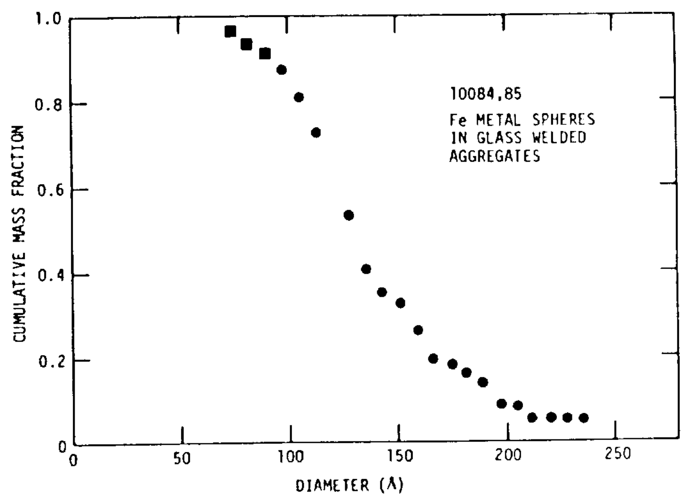


Fig. 22. Size distribution of Fe^0 metal spheres in agglutinitic glass from Apollo 11 sample 10084. Data are from TEM photographs. The squares are for sizes <40 Å, which are too small to be counted with any certainty. Modified from *Housley et al.* (1974).

It was suggested that the variations in Fe^0 contents of individual soils might be due to differences in exposure time to the solar wind and to meteoritic flux. That is, the amount of solar-wind-implanted reducing gases and impact reworking was a function of time. This was based upon rough correlations of Rb-Sr and Pb^{207}-Pb^{206} ages vs. Fe^0 content of soils. Although this apparent correlation was not real, it prompted other workers to study the origin of Fe metal particles in lunar samples. Thus, the concept of "exposure age" for a lunar soil was established as a function of the length of time of reworking at the lunar surface. To sedimentologists, this can be correlated with soil maturity.

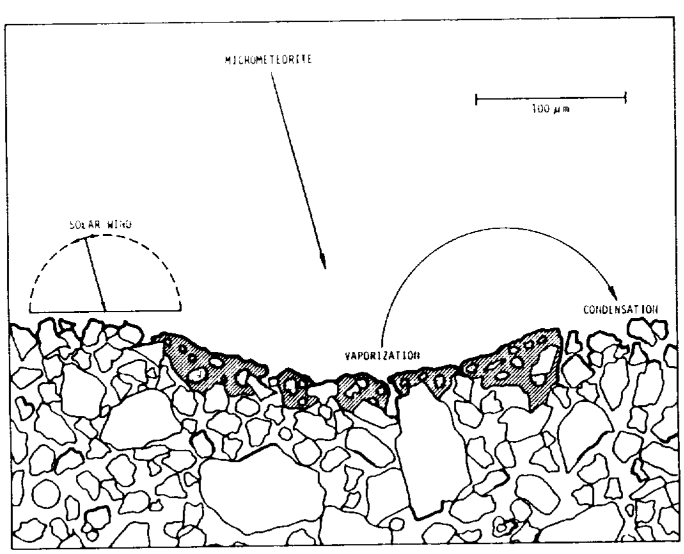


Fig. 21. Schematic representation of lunar soil formation.

I_s/FeO AS A MEASURE OF SOIL MATURITY

The ferromagnetic resonance spectra of all lunar soils are dominated by a signal due to fine-grained Fe^0 particles (40-330 Å). The intensity of this signal is designated as I_s. It was suggested that this FMR intensity, normalized to the total Fe content (I_s/FeO), might be a measure of the relative surface exposure age of lunar soils. It is necessary to include FeO in this index because the amount of Fe^0 generated by micrometeorite-impact autoreduction is a function, to some extent, of the FeO of the silicate liquid formed from the melting of the soil.

Effectively, as the duration of exposure at the lunar surface increases, so does the amount of solar-wind-implanted species, and the agglutinate content increases with an accompanying increase in the Fe^0 metal (reflected in the increase I_s/FeO). Thus, the range of I_s/FeO for immature, submature, and mature levels of soil development is roughly equivalent to the same classification in terms of petrographic agglutinates, as well as mean grain size, for Apollo 17 soils. As explained above, an increase in I_s/FeO is a function of agglutinate content (Fig. 23), which in turn is a function of maturity (exposure) of a soil. This concept of

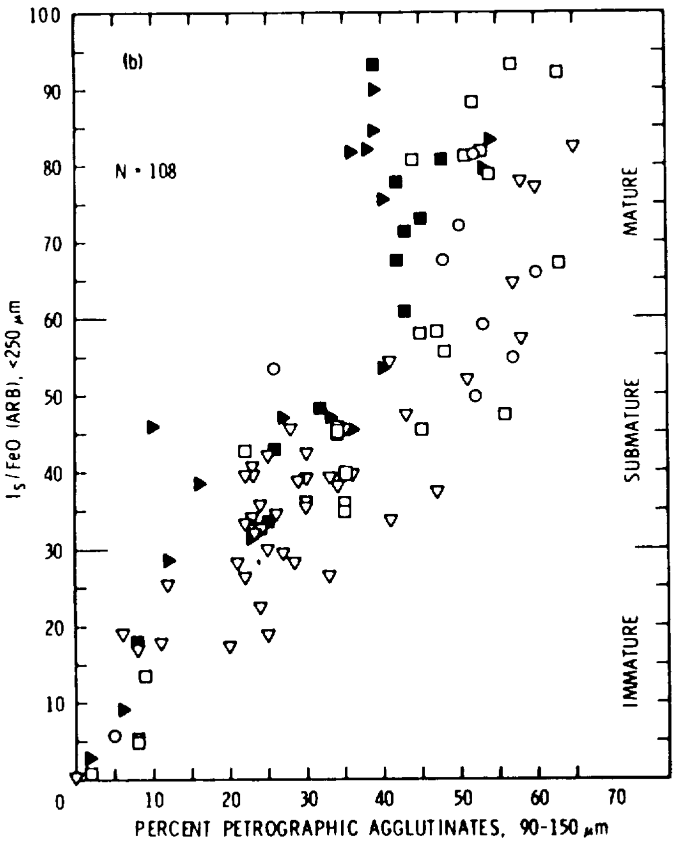


Fig. 23. Correlation of I_s/FeO with agglutinate contents of soils as determined by point counting with a petrographic microscope. Samples are from all Apollo missions. The legend for the symbols used here is given in Fig. 24. Figure modified from *Morris* (1976).

exposure age showed that for some soils, I_s/FeO correlates with trapped ^{36}Ar. Thus, the parameter I_s/FeO is an effective index of soil maturity, which is a function of surface exposure age.

I_s/FeO AS A MEASURE OF SOLAR-WIND ELEMENTAL CONCENTRATIONS IN LUNAR SOILS

Morris (1976) measured I_s/FeO for the <25-μm-size fraction of 152 soils and for the 90-150-μm-size fraction of 88 soils. With this large suite of samples, it was possible to correlate I_s/FeO with a variety of other indices of surface exposure. For example, implanted N, C, and the gases ^{4}He and ^{36}Ar were shown to increase in concentration with increasing I_s/FeO values. Figure 24 shows the direct correlation of I_s/FeO (i.e., exposure age) with the contents of C and ^{4}He. However, of what practical use are the I_s/FeO values of lunar soils?

Nuclear fusion is a highly desirable source of energy because of its small amounts of radioactive products, and lunar soils are an extremely important source of ^{3}He, the most highly prized of the fusion reactants. This solar-wind-implanted species can be correlated with the more abundant ^{4}He. Figure 24 shows I_s/FeO vs. ^{4}He contents of several soils. At first glance, the ^{4}He correlation

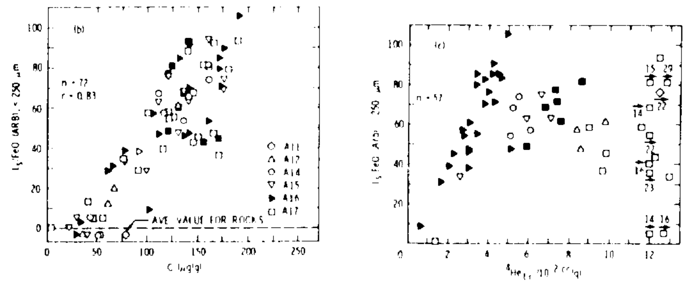


Fig. 24. Correlation of I_s/FeO with solar-wind gases. Figure has been modified from *Morris* (1976).

does not appear to be very good, but when the Apollo 17 soils are omitted, the correlation is good; in fact, it is almost the same as for C vs. I_s/FeO (also Fig. 24). The Apollo 17 soils are derived from high-Ti basalts and contain up to 14% ilmenite ($FeTiO_3$). Ilmenite appears to be a "sponge" (sink) for ^{4}He. Therefore, even immature Apollo 17 soils have enough exposure to solar wind to pick up and retain appreciable amounts of ^{4}He. The Apollo 17 soils with higher FeO contents (open squares on Fig. 24) have the highest ^{4}He contents; thus, the FeO content would seem to be indicative of the ilmenite content (*Taylor*, 1990).

Correlations also exist for ^{40}Ar/^{36}Ar and exposure age of soils. The trapped rare gases ^{4}He, ^{20}Ne, ^{36}Ar, ^{84}Kr, and ^{132}Xe are those gases that originate directly from the solar wind and not from nuclear reactions. Various studies have attempted to quantify the absolute rate of soil formation. These include use of cosmogenic radionuclides ^{22}Na, ^{26}Al, and ^{53}Mn, as well as "track densities." Based upon isotopic data, it is generally agreed that the rates of fine-grained lunar soil (<1 mm) formation are much less than 1 cm/yr.

The most detailed investigations applying I_s/FeO measurements on lunar soils were performed on core samples taken during the Apollo missions, particularly 15-17. Horizons of mature soil (high I_s/FeO) were discovered in these soil profiles. These mature soil layers are the result of slow formation with extensive reworking ("gardening") in the upper few centimeters or so of the regolith, a process termed "*in situ* reworking." However, large meteorite impacts obliterate or bury the "*in situ*" (i.e., mature) horizons so that the soil profile as revealed in cores does not represent continuous slow deposition, but sporadic events intermixed with periods of quiescent soil development. It was recognized that the units in the cores may be only discontinuous pods, rather than layers with horizontal extent and time significance. The unraveling of the secrets hidden within the soils is complicated and research continues today. However, the concept of I_s/FeO has proven to be one of the most useful in lunar science and will be of use for various commercial endeavors involved with a lunar base.

SUMMARY

The various constituents of the Moon, namely the rocks, minerals, and glasses, will be among the raw materials used to construct a lunar base. The lunar regolith, the fragmental material present on the surface, is composed mostly of disaggregated rocks and minerals, but also includes glassy fragments fused together by impacts. The finer fraction of the regolith (i.e., <1 cm),

informally referred to as soil, is probably the most important portion of the regolith for use at a lunar base. This soil can be used as insulation against cosmic rays, for lunar ceramics and abodes, for growing plants, for the extraction of valuable elements, etc. The soil contains abundant solar-wind-implanted elements, as well as various minerals, particularly oxide phases, that are of potential economic importance. For example, these components of the soil are sources of oxygen and hydrogen for rocket fuel, helium for nuclear energy, and metals such as Fe, Al, Si, and Ti, for construction. The peculiar impact-melt products in the soil called agglutinates are a function of the soil's maturity. These agglutinates contain tremendous quantities of metallic Fe. The FMR signature of a soil, I_s/FeO, measures the amount of agglutinates, which increases as maturity increases. As exposure at the lunar surface increases (i.e., maturity), the amount of absorption of solar-wind products also increases. Thus, the I_s/FeO signature is indicative of the relative amounts of solar-wind-implanted elements, notably He and H, in the lunar soil. It is obvious that a thorough knowledge of all aspects of the lunar regolith is requisite to any efficient plans for colonizing the Moon.

APPENDIX

Obtaining Lunar Samples

The lunar sample collection is a national treasure, and the samples must be preserved and curated with concern for their integrity. This entails the frugal use of samples for various purposes, usually scientific. Therefore, before samples are allocated, it must be determined that every attempt has been made to (1) use analog samples, either synthetic or natural (e.g., terrestrial or meteoritic specimens) and (2) design experiments such that the smallest amount of lunar material is needed without jeapardizing the quality of the results. In order to formally apply for allocation of lunar materials, it is necessary to write a short proposal to the Planetary Materials Curator. This proposal should address (1) the nature of the experiment to be conducted, particularly with respect to its scientific and/or engineering merits; (2) preliminary results obtained on analog samples; (3) consideration of the mass and size of the samples needed; (4) the specific sample number requested (as best as can be determined); (5) the credentials of the principal investigator and research associates; and (6) a description of the facilities necessary for conducting the experiment. Depending upon the individual situation, there may be some additional information needed; therefore, the Planetary Materials Curator should be contacted before submitting any request. Upon receipt of the sample request, the proposal will be reviewed by the Lunar and Planetary Sample Team (LAPST), who will make a recommendation to NASA concerning the request. It should be emphasized that the Planetary Materials Curator and his staff will make every effort to assist an individual in obtaining the proper sample, if the experiment merits its use.

Catalogs and Documents on Lunar Samples

There are many catalogs and documents about lunar samples that are not commonly known to the public. Following is a compilation of many of these publications, several of which are NASA publications and can be obtained by writing to

Planetary Materials Coordinator
NASA Johnson Space Center - Code SN2
Houston TX 77058
(713) 483-3274

Lunar Sample Documents

Apollo 11

Preliminary Examination of Lunar Samples from Apollo 11. *Science, 165,* 1211-1227. (Lunar Sample Preliminary Examination Team, 1969.)

Geologic Setting of the Lunar Samples Returned with Apollo 11. (Shoemaker E. M. et al., 1969.)

Apollo 11 Preliminary Science Report. *NASA SP-214,* 1969.

Lunar Sample Information Catalog Apollo 11. Lunar Receiving Laboratory, Science and Applications Directorate, MSC, NASA, 1969.

Apollo 11 Organic Contamination History. (Flory D. A., Simoneit B. R., and Smith D. H., 1969)

Lunar Surface Closeup Stereoscopic Photography on the Sea of Tranquility. *NASA TMX-58077.* (Greenwood W. R. et al., 1971.)

Apollo 11 Lunar Sample Information Catalog (Revised). *JSC 12522.* (Kramer F. E. et al., 1977.)

Apollo 12

Preliminary Examination of Lunar Samples from Apollo 12. *Science, 167,* 1325-1339. (Lunar Sample Preliminary Examination Team, 1970.)

Apollo 12 Preliminary Science Report. *NASA SP-235,* 1970.

Apollo 12 Lunar-Sample Information. *NASA TRR-353.* (Warner J., 1970.)

Electron Microprobe Analyses of Minerals from Apollo 12 Lunar Samples. *Univ. New Mexico Spec. Publ. No. 3.* (Busche F. D. et al., 1971.)

Apollo 12 Coarse Fines (2-10 mm): Sample Locations, Description, and Inventory. *NASA JSC 14434.* (Marvin U. B., 1979.)

Apollo 14

Preliminary Examination of Lunar Samples from Apollo 14. *Science, 173,* 681-693. (Lunar Sample Preliminary Examination Team, 1971.)

Apollo 14 Preliminary Science Report. *NASA MSC SP-272,* 1971.

Apollo 14 Lunar Sample Information Catalog. *NASA MSC TMX-58062.* (Lunar Sample Curator's Office, 1971.)

Lunar Surface Closeup Stereoscopic Photography at Fra Mauro (Apollo 14). *NASA JSC TMX-58072.* (Carrier W. D. and Heiken G., 1972.)

Description, Classification, and Inventory of the Comprehensive Sample from Apollo 14. *NASA JSC.* (Phinney W. et al., 1975.)

Apollo 14 Coarse Fines (4-10 mm) Sample Location and Classification. *NASA JSC 12922.* (Kramer F. E. and Twedell D. B., 1977.)

Geology of the Apollo 14 Landing Site in the Fra Mauro Highlands. *U.S. Geol. Surv. Prof. Pap. 880.* (Swann G. A. et al., 1977.)

Lithological Maps of Selected Apollo 14 Breccia Samples. *NASA JSC 13842.* (Twedell D. et al., 1977.)

Apollo 14 Rock Samples. *NASA JSC 14240.* (Carlson I. C. and Walton J. A., 1978.)

Apollo 15

Apollo 15 Preliminary Science Report. *NASA MSC SP-289,* 1972.

Apollo 15 Lunar Samples—Collection of Papers. *Science, 175,* 1972.

Apollo 15 Coarse Fines (4-10 mm): Sample Classification, Description, and Inventory. *NASA MSC 03228.* (Powell B. N., 1972.)

Documentation of Apollo 15 Samples. *U.S. Geol. Surv. Interagency Rept. 47.* (Sutton R. L. et al., 1972.)

Lunar Sample Information Catalog Apollo 15. *NASA MSC 03209.* (Lunar Receiving Laboratory, 1972.)

Apollo 15 Rake Sample Microbreccias and Non-Mare Rocks: Bulk Rock, Mineral and Glass Electron Microprobe Analyses. *Univ. New Mexico Spec. Publ. No. 11.* (Hlava P. F. et al., 1973.)

Electron Microprobe Analyses of Spinel Group Minerals and Ilmenite in Apollo 15 Rake Samples of Igneous Origin. *Univ. New Mexico Spec. Publ. No. 10.* (Nehru C. E. et al., 1973.)

Apollo 15 Deep-Drill-Core: Classification, Description, and Inventory of Separated Particles. *NASA JSC.* (Drake M. J., 1974.)

Catalog of Apollo 15 Rocks: Parts 1, 2, and 3. *Curatorial Branch Publ. No. 72, JSC 20787.* 1296 pp. (Ryder G., 1985.)

Workshop on the Geology and Petrology of the Apollo 15 Landing Site. *LPI Tech. Rpt. 86-03.* 126 pp. (Spudis P. D. and Ryder G., 1986.) Lunar and Planetary Institute, Houston.

Apollo 16

Apollo 16 Preliminary Science Report. *NASA SP-315,* 1972.

Apollo 16 Coarse Fines (4-10 mm): Sample Classification, Description, and Inventory. *NASA MSC.* (Marvin U. B., 1972.)

Apollo 16 Rake Samples 67515 and 68537 Sample Classification, Description, and Inventory. *NASA MSC.* (Smith J. V. and Steele I. M., 1972.)

Description, Classification, and Inventory of 151 Apollo 16 Rake Samples from the LM Area and Station 5. *NASA MSC.* (Keil K. et al., 1972.)

Lunar Sample Information Catalog Apollo 16 Lunar Receiving Laboratory. *NASA MSC 03210.* (Butler P., 1972.)

Description, Classification, and Inventory of Apollo 16 Rake Samples from Stations 1, 4, and 13. *NASA JSC.* (Phinney W. and Lofgren G., 1973.)

The Apollo 16 Lunar Samples: Petrographic and Chemical Description. *Science, 179,* 23-34. (Apollo 16 Preliminary Examination Team, 1973.)

Catalog of Apollo 16 Rake Samples from the LM Area and Station 5. *Univ. New Mexico Spec. Publ. No. 13.* (Warner R. D. et al., 1976.)

Catalog of Pristine Non-Mare Materials Part 1. Non-Anorthosites Revised. *NASA JSC 14565.* (Ryder G. and Norman M. D., 1979.)

Catalog of Pristine Non-Mare Materials Part 2. Anorthosites Revised. *NASA JSC 14603.* (Ryder G. and Norman M. D., 1979.)

Apollo 16 Soil Catalog 61220 Classification and Description of 1-4 mm Fines. *NASA JSC Curatorial Branch Publ. No. 53.* (Marvin U. B. and Mosie A. B., 1980.)

Catalog of Apollo 16 Rocks Part 1. 60015-62315. *NASA JSC 16904, Curatorial Branch Publ. No. 52.* (Ryder G. and Norman M. D., 1980.)

Catalog of Apollo 16 Rocks Part 2. 63335-66095. *NASA JSC 16904, Curatorial Branch Publ. No. 52.* (Ryder G. and Norman M. D., 1980.)

Catalog of Apollo 16 Rocks Part 3. 67015-69965. *NASA JSC 16904, Curatorial Branch Publ. No. 52.* (Ryder G. and Norman M. D., 1980.)

Geology of the Apollo 16 Area, Central Lunar Highlands. *U.S. Geol. Surv. Prof. Pap. 1048.* (Ulrich G. E. et al., 1981.)

Workshop on Apollo 16. *LPI Tech. Rept. 81-01.* (James O. B. and Hörz F., eds., 1981.) Lunar and Planetary Institute, Houston.

Regolith Breccia Workbook. *NASA JSC 19045.* (Fruland R. M., 1983.)

Apollo 17

Apollo 17 Lunar Samples: Chemical and Petrographic Description. *Science 182,* 659-672. (Apollo 17 Preliminary Examination Team, 1973.)

Apollo 17 Preliminary Science Report. *NASA JSC SP-330,* 1973.

Apollo 17 Coarse Fines (4-10 mm) Sample Location, Classification, and Photo Index. *NASA JSC.* (Meyer C., 1973.)

Apollo 17 Results. *Eos Trans AGU, 54,* 580-622. (Bence A. E., ed., 1973.)

Geologic Exploration of Taurus-Littrow: Apollo 17 Landing Site. *Science, 182,* 672-680. (Apollo Field Geology Investigation Team, 1973.)

Lunar Sample Information Catalog Apollo 17. *NASA MSC-03211.* (Lunar Receiving Laboratory, 1973.)

Description, Classification, and Inventory of Apollo 17 Rake Samples from Station 6. *NASA JSC.* (Phinney W. et al., 1974.)

Description, Classification, and Inventory of 113 Apollo 17 Rake Samples from Stations 1A, 2, 7, and 8. *NASA JSC.* (Keil K. et al., 1974.)

Interdisciplinary Studies of Samples from Boulder 1, Station 2, Apollo 17, Vol. 1; Vol 2. *Smithsonian Astrophys. Obser.* (Adams J. B. et al., 1974.)

Electron Microprobe Analysis of Spinel, Fe-Ti Oxides and Metal from Apollo 17 Rake Sample Mare Basalts. *Univ. New Mexico Spec. Publ. No. 16.* (Warner R. D. et al., 1976.)

Electron Microprobe Analysis of Olivine, Pyroxene, and Plagioclase from Apollo 17 Rake Sample Mare Basalts. *Univ. New Mexico Spec. Publ. No. 16.* (Warner R. D. et al., 1976.)

Catalog of Apollo 17 Rake Samples from Stations 1A, 2, 7, and 8. *Univ. New Mexico Spec. Publ. No. 15.* (Warner R. D. et al., 1978.)

Catalog of Lunar Mare Basalts Greater than 40 Grams Part 1. Major and Trace Element Chemistry. *LPI Contr. 438.* (Lofgren G. E. and Lofgren E. M., 1981.) Lunar and Planetary Institute, Houston.

Guidebook for the Boulders at Station 6, Apollo 17. *NASA JSC-17243, Curatorial Branch Publ. No. 55.* (Phinney W., 1981.)

The Geologic Investigation of the Taurus Littrow Valley: Apollo 17 Landing Site (Maps). *U.S. Geol. Surv. Prof. Pap. 1080.* (Wolfe E. W. et al., 1981.)

Luna 16

Issue Especially Devoted to the Study of Some Luna 16 Samples. *Earth Planet. Sci. Lett., 13,* 223-472. 1972.

Luna 20

Issue Espcially Devoted to the Study of Some Luna 20 Samples. *Earth Planet. Sci. Lett., 17,* 1-294. 1972.

Luna 20—A Study of Samples from the Lunar Highlands Returned by the Unmanned Luna 20 Spacecraft. *Geochim. Cosmochim. Acta, 37,* 719-1110. (Anders E. and Albee A. L., 1973.)

Further Advances in Lunar Research: Luna 16 and 20 Samples. *India Nat. Sci. Acad.,* New Delhi. (Bhandari N. and Rao M. N., eds., 1974.)

Luna 24

Luna 24 Samples Presented to the USA: Catalog and Preliminary Description. *NASA JSC.* (Nagle J. S. and Walton W. J. A., 1977.)

Preliminary Data for the Regolith Core Brought to Earth by the Automatic Lunar Station Luna 24. *Proc. Lunar Sci. Conf. 8th,* 3303-3318. (Barsukov V. L., 1977.)

Mare Crisium: The View from Luna 24. (Papike J. J. and Merrill R. B., 1978.) Pergamon, New York.

Guidebooks

Breccia Guidebook No. 1-14321. *NASA JSC 14753.* (Meyer C. and King C. D., 1979.)

Breccia Guidebook No. 2-66095. *NASA JSC 16198.* (Garrison J. R. and Taylor L. A., 1979.)

Breccia Guidebook No. 3-67915. *NASA JSC 16242.* (Taylor G. J. and Mosie A. B., 1979.)

Breccia Guidebook No. 4-67015. *NASA JSC 16671.* (Marvin U. B., 1980.)

Breccia Guidebook No. 5-14305. *NASA JSC 19267.* (Shervais J. W. and Taylor L. A., 1983.)

Breccia Guidebook No. 6-67435. *NASA JSC 18743.* (Taylor G. J. and Mosie A. B., 1982.)

Breccia Guidebook No. 7-14321. *NASA JSC 19492.* (Shervais J. W., Knapp S., and Taylor L. A., 1984.)

Breccia Guidebook No. 8-72275. *NASA JSC 20416.* (Salpas P. A., Willis K. J., and Taylor L. A., 1985.)

Guidebook for Lunar Breccia 67016. *NASA JSC 17393.* (Norman M. D. and Garcia G. G., 1981.)

Guidebook for the Boulders at Station 6, Apollo 17. *NASA JSC 17243.* (Phinney W., 1981.)

Publications on Cores

Description, Dissection, and Subsampling of Apollo 14 Core Sample 14230. *NASA TMX-58070.* (Fryxell R. and Heiken G., 1971.)

Description of Core Samples Returned by Apollo 12. *NASA TMX-58066.* (Lindsay J. F. et al., 1971.)

Stratigraphy of the Apollo 15 Drill Core. *NASA TMX-58101.* (Heiken G. et al., 1972.)

Lunar Core Catalog. *NASA JSC 09252.* (Duke M. B. and Nagle J. S., 1976.)

Drive Tubes 74002/74001 Dissection and Description. *NASA JSC, Curatorial Branch Publ.* (Nagle J. S., 1978.)

Introduction to the Core Samples from the Apollo 16 Landing Site. *NASA JSC 17659.* (Fruland R. M. and Reimold J. N., 1981.)

Table of Sample Depths for Apollo 15, 16, and 17 Drill Cores. *NASA JSC, Curatorial Branch Publ. No. 56.* (Allton J. et al., 1981.)

Catalog of the Apollo 16 Lunar Core 60009/60010. *NASA JSC 17172.* (Fruland R. M. et al., 1982.)

Publications on Soils

A Catalog of Lunar Soils. *NASA JSC, Curatorial Branch Publ.* (Heiken G., 1974.)

Petrology of Lunar Soils. *Rev. Geophys. Space Phys., 13,* 567-587. (Heiken G., 1975.)

Lunar Stratigraphy and Sedimentology. Elsevier Sci. Publ. Co., 302 pp. (Lindsay J. F., 1976.)

Occurrence of ANT Fragments in Lunar Soils and Breccias: Guide to Polished Thin Sections. *NASA JSC 14394.* (Bickel C. E. and Warner J. L., 1978.)

The Lunar Regolith. *Rev. Geophys. Space Phys., 20,* 761-826. (Papike J. J. et al., 1982.)

Handbook of Lunar Soils Part 1: Apollo 11-15. *NASA JSC 19069.* (Morris R. V. et al., 1983.)

Handbook of Lunar Soils Part 2: Apollo 16-17. *NASA JSC 19069.* (Morris R. V. et al., 1983.)

Acknowledgments. I would like to thank my good Tennessee friend Jack Daniels for the inspiration that he has provided to me on numerous occasions, e.g., while compiling the data for this review paper. Any and all mistakes were originally due to his influence. However, this final version of the manuscript has been improved immensely by the conscientiously thorough and critical reviews of two highly respected colleagues, Graham Ryder and Paul Spudis. A portion of this endeavor was supported by NASA Grant 9-62.

REFERENCES

Anderson A. T. et al. (1970) Armalcolite: A new mineral from the Apollo 11 samples. *Proc. Apollo 11 Lunar Sci. Conf.,* pp. 55-63.

BVSP (Basaltic Volcanism Study Project) (1981) *Basaltic Volcanism on the Terrestrial Planets.* Pergamon, New York. 1286 pp.

El Goresy A., Ramdohr P., and Taylor L. A. (1971) The opaque minerals in the lunar rocks from Oceanus Procellarum. *Proc. Lunar Sci. Conf. 2nd,* pp. 219-235.

Frondel J. W. (1975) *Lunar Mineralogy.* Wiley, New York. 323 pp.

Gibson M. A. and Knudsen C. W. (1985) Lunar oxygen production from ilmenite. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 543-550. Lunar and Planetary Institute, Houston.

Goldstein J. I. and Yakowitz H. (1971) Metallic inclusions and metal particles in the Apollo 12 lunar soil. *Proc. Lunar Sci. Conf. 2nd,* pp. 177-191.

Haggerty S. E. (1972) Luna 16: An opaque mineral study and a systematic examination of compositional variations of spinels from Mare Fecunditatis. *Earth Planet. Sci. Lett., 13,* 328-352.

Haggerty S. E. (1973) Armalcolite and genetically associated opaque minerals in the lunar samples. *Proc. Lunar Sci. Conf. 4th,* pp. 777-797.

Housley R. M., Cirlin E.-H., Paton N. E., and Goldberg I. B. (1974) Solar wind and micrometeorite alteration of the lunar regolith. *Proc. Lunar Sci. Conf. 5th,* pp. 2623-2642.

Misra K. C. and Taylor L. A. (1975) Characteristics of metal particles in Apollo 16 rocks. *Proc. Lunar Sci. Conf. 6th,* pp. 615-639.

Morris R. V. (1976) Surface exposure indices of lunar rocks: A comparative FMR study. *Proc. Lunar Sci. Conf. 7th,* pp. 315-335.

Papike J. J. and Bence A. E. (1979) Planetary basalts: Chemistry and petrology. *Rev. Geophys. Space Phys., 17,* 1612-1641.

Papike J. J. and Vaniman D. T. (1978) Luna 24 ferrobasalts and the mare basalt suite: Comparative chemistry, mineralogy, and petrology. In *Mare Crisium: The View from Luna 24* (J. J. Papike and R. B. Merrill, eds.), pp. 371-401. Pergamon, New York.

Papike J. J., Simon S. B., and Laul J. C. (1982) The lunar regolith: Chemistry, mineralogy, and petrology. *Rev. Geophys. Space Phys., 20,* 761-826.

Papike J. J., Hodges F. N., Bence A. E., Cameron M., and Rhodes J. M. (1976) Mare basalts: Crystal chemistry, mineralogy, and petrology. *Rev. Geophys. Space Phys., 14,* 475-540.

Smith J. V. (1974) Lunar mineralogy: A heavenly detective story presidential address, Part I. *Am. Mineral., 59,* 231-243.

Smith J. V. and Steele I. M. (1976) Lunar mineralogy: A heavenly detective story, Part II. *Am. Mineral., 61,* 1059-1116.

Stöffler D. et al. (1980) Recommended classification and nomenclature of lunar highland rocks—A committee report. *Proc. Conf. Lunar Highlands Crust* (J. J. Papike and R. B. Merrill, eds.), pp. 51-70. Pergamon, New York.

Taylor L. A. (1990) Hydrogen, helium, and other solar-wind components in lunar soil: Abundances and predictions. *Proc. Space 90,* 68-77. Aerospace/ASCE, Albuquerque.

Taylor L. A. and Cirlin E.-H. (1986) A review of ESR studies on lunar samples. In *ESR Dating and Dosimetry* (M. Ikeya and T. Miki, eds.), pp. 19-38. Ionics, Tokyo.

Taylor L. A. and Oder R. R. (1990) Magnetic beneficiation of highland and high-Ti mare soils: Rocks, mineral, and glassy components. *Proc. Space 90,* 143-152. Aerospace/ASCE, Albuquerque.

Taylor L. A., Williams R. J., and McCallister R. H. (1972) Stability relations of ilmenite and ulvöspinel in the Fe-Ti-O system and application of these data to lunar mineral assemblages. *Earth Planet. Sci. Lett., 16,* 282-288.

Taylor S. R. (1975) *Lunar Science: A Post-Apollo View.* Pergamon, New York. 372 pp.

Taylor S. R. (1982) *Planetary Science: A Lunar Perspective.* Lunar and Planetary Institute, Houston. 481 pp.

Wilhelms D. E. (1984) Moon. In *The Geology of the Terrestrial Planets* (M. H. Carr, ed.), pp. 106-205. NASA SP-469.

Williams R. J. (1985) Oxygen extraction from lunar materials: An experimental test of an ilmenite reduction process. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 551-558. Lunar and Planetary Institute, Houston.

Williams R. J., McKay D. S., Giles D., and Bunch T. E. (1979) Mining and beneficiation of lunar ores. In *NASA SP-428,* pp. 275-288.

N93-13974

THE FORMATION OF ORE MINERAL DEPOSITS ON THE MOON: A FEASIBILITY STUDY

Lawrence A. Taylor and Fengxiang Lu[1]

Department of Geological Sciences
University of Tennessee
Knoxville TN 37996

Most of the ore deposits on Earth are the direct result of formation by hydrothermal solutions. Analogous mineral concentrations do not occur on the Moon, however, because of the absence of water. Stratified ore deposits form in layered instrusives on Earth due to fractional crystallization of magma and crystal settling of high-density minerals, particularly chromium in the mineral chromite. We have evaluated the possibility of such mineral deposition on the Moon, based upon considerations of "particle settling velocities" in lunar vs. terrestrial magmas. A first approximation of Stoke's Law would seem to indicate that the lower lunar gravity (1/6 terrestrial) would result in slower crystal settling on the Moon. However, the viscosity of the silicate melt is the most important factor affecting the settling velocity. The viscosities of typical lunar basaltic melts are 10-100 times less than their terrestrial analogs. These lower viscosities result from two factors: (1) lunar basaltic melts are typically higher in FeO and lower in Al_2O_3, Na_2O, and K_2O than terrestrial melts; and (2) lunar igneous melts and phase equilibria tend to be 100-150°C higher than terrestrial, largely because of the general paucity of water and other volatile phases on the Moon. Therefore, particle settling velocities on the Moon are 5-10 times greater than those on Earth. It is highly probable that stratiform ore deposits similar to those on Earth exist on the Moon. The most likely ore minerals involved are chromite, ilmenite, and native FeNi metal. In addition, the greater settling velocities of periodotite in lunar magmas indicate that the buoyancy effects of the melt are less than on Earth. Consequently, the possibility is considerably less than on Earth of deep-seated volcanism transporting upper mantle/lower crustal xenoliths to the surface of the Moon, such as occurs in kimberlites on Earth.

INTRODUCTION

On Earth, minerals commonly occur in economically recoverable concentrations called ore deposits. The various mechanisms that bring about these mineral concentrations are largely the subject of the field of economic geology. Inherent in the usage of the term "ore deposit" is that one or more metals can be extracted from the ore "at a profit." At this stage in the development of lunar base concepts, it is difficult to foresee the exact needs or economics of any such lunar endeavor. It is probable that we will never mine ores on the Moon in order to bring the metals back to Earth. However, there are certain minerals known to be present on the Moon that will undoubtedly be used almost immediately by the early lunar settlements, minerals such as native FeNi for structural purposes, and ilmenite ($FeTiO_3$) for oxygen production. In addition, other oxide minerals such as chromite ($FeCr_2O_4$) and ulvöspinel (Fe_2TiO_4) may be used for their oxygen or metal contents.

Most of the ore minerals on Earth are sulfides and oxides and are called "opaque minerals" because they do not pass light even in thin section. These concentrations of ore minerals most commonly result from deposition by hydrothermal solutions (i.e., 100-300°C watery solutions). The Moon does not possess appreciable amounts of water, if any; therefore, the presence of ore minerals deposited by hydrothermal solutions is improbable. However, there are other means of depositing ore minerals [e.g., chromite, ilmenite, Platinum Group Elements (PGE)] that are based on fractional crystallization and crystal settling.

Crystallizing minerals will settle within a melt if their densities are greater than the melt. On Earth such accumulations are commonly found in layered intrusions and are known as stratiform deposits. In fact, the mineral chromite ($FeCr_2O_4$), which constitutes the world's major source of the strategic metal, chromium, occurs in mafic strata of large layered igneous complexes often associated with PGE. However, only three layered intrusives—the Bushveld of Transvaal, the Great Dyke of Rhodesia, and the Stillwater Complex of Montana—are known to contain substantial amounts of chromite.

Layered complexes such as the Stillwater originate as large igneous intrusions where the slow cooling of the melt results in fractional crystallization leading to the settling of successive layers of crystals on the progressively rising floor of the intrusive sheet. Related silicate mineral assemblages embrace almost the complete range of mafic and ultramafic rocks: peridotite, dunite, pyroxenite, norite, and to a lesser extent, gabbro and anorthosite. In fact, the presence of such rocks is evidence that fractional crystallization and gravity-controlled crystal settling have been effective. On the Moon, anorthosites, gabbros, troctolites, etc. are common and point to fractional crystallization as a real process. Therefore, it is worth speculating on the possibility of stratiform ore deposits on the Moon.

LUNAR VS. TERRESTRIAL SILICATE MELTS

Introduction

The nonmare portions of the Moon, the highlands, consist of just the rock types that one would expect from fractional crystallization and crystal settling (or floating, in the case of plagioclase on the Moon). In fact, the concept of the Lunar Magma Ocean contends that the outer 200-400 km of the Moon

[1]Now at China University of Geoscience, Wuhan 430074, P.R. China

was molten during the first 100 m.y. after formation. As this magma slowly cooled, the plagioclase that crystallized floated to form "rockbergs" that ultimately coalesced to form the lunar crust. The mafic minerals (e.g., olivine and pyroxene) sank to form the mantle/lower crust, which later gave rise, by partial melting, to basaltic magmas. Such a scenario for lunar evolution implies that the same processes occurred in the igneous plutons of the Moon that occurred on the Earth.

Whether deposits of such minerals as chromite, formed by crystal settling, occur on the Moon is unknown because the Moon remains largely unexplored. Only a few of the nine sites (six from Apollo and three from Luna) visited have been sampled to any geographic extent, and the meager remote-sensing data we possess is of neither sufficient quality nor quantity to fully characterize the lunar surface. It would be unlikely that such data coverage of the surface of the Earth would reveal the presence of ore bodies; therefore, it is not surprising that ores have not been sampled on the Moon. However, the igneous activity of the early Moon suggests that accumulations of chromite, ilmenite, native FeNi metal, etc. are to be expected. Or are they?

Settling Velocities

With gravity on the Moon only one-sixth that of Earth, one would suppose that the effective settling velocities of phases in a lunar melt will be reduced. The settling velocity of a crystal in a melt can be approximated by considerations of Stoke's Law, an equation relating settling velocity to various parameters

$$V = \frac{2ga^2(d_1 - d_2)}{9\eta}$$

where V is the velocity of crystal settling in cm/sec; g is the acceleration of gravity in cm/sec^2; a is the diameter of the particle in cm; d is the density of solid (1) or liquid (2) in gm/cm^3; and η is the viscosity of the liquid ($dyne\text{-}sec/cm^2$ or poise).

The most important factors to be considered here are (1) the acceleration of gravity, g, which directly affects settling rate; (2) the difference in density between the crystal and the melt; and (3) the viscosity, η, of the silicate melt, which inversely affects the velocity. As we know, the acceleration of gravity on the Moon's surface is about 160 cm/sec^2, compared to 980 cm/sec^2 on Earth. This factor will contribute sixfold less to the settling velocity for the lunar situation, all other factors being equal. The viscosity differences between silicate melts on the Moon and the Earth are related primarily to two parameters: (1) the average temperature of a lunar mare basalt liquidus and solidus is 100-150°C higher, caused by the paucity of water and other mineralizers that have a tendency to flux the melt; and (2) the typical lunar mare basalt is considerably higher in FeO and lower in Al_2O_3, Na_2O, and K_2O than its terrestrial counterpart.

We have performed an analysis of the various parameters that affect settling velocity for both terrestrial and lunar magmas. Representative types of terrestrial basalts, including one for the Stillwater magma and a Mg-rich basanite (Si-deficient olivine basalt), and selected mare basalts from various missions were selected for this analysis. Mare basalts were chosen for this study for two basic reasons:

1. Of the sampled rocks from the Moon, it is the mare basalts that contain the greatest concentrations of ilmenite, chromite, and native FeNi. These minerals commonly are early to crystallize during cooling of the magma, such that the effects of crystal settling would be least impaired by too much crystallization.

2. We have good knowledge of the nature of mare basins and their mare basalt fillings. It is probable that the basalts that we see at the surface came from magma chambers at shallow depths beneath the mare (e.g., 1-15 km). These chambers were supplied by basaltic melt from even greater depths. *Schultz* (1976) has presented various scenarios of basin formation and associated volcanism that depict the types of situations to which we are referring. It is the near-surface magmatic occurrences forming hypabyssal to shallow plutonic igneous regimes that are the subject of this study. They are close enough to the lunar surface to be potentially accessible and usable.

The densities and viscosities of the silicate melts (Tables 1 and 2) were calculated using the method and data of *Bottinga and Weill* (1970, 1972). The viscosities of the terrestrial melts were estimated at 1200°C, vs. 1300°C for lunar, because of the lack of fluxing components in the lunar melts, as mentioned above.

The settling velocities of various 1-cm spherical particles were calculated using Stoke's equation, given above, and are presented in Table 3 and Fig. 1. The values for the acceleration of gravity used were 160 and 980 cm/sec^2 for the Moon and Earth, respectively. This equation is for pure newtonian fluids. In reality, silicate melts can behave plastically once significant crystallization has occurred. However, for the purposes of this study, which is one of relative values, not absolutes, Stoke's Law should suffice.

The settling velocities were calculated for (1) ilmenite, (2) chromite, and (3) a peridotite xenolith. The periodotite was included in order to evaluate the possibility of abundant upper mantle/lower crustal xenoliths in lunar basalts, such as those that occur in kimberlites and alkali basalts on Earth. The density of the chromite used in the calculations was different for the Earth and Moon situations (Table 3). On the Moon, chromites most commonly contain ulvöspinel (Fe_2TiO_4) in solid solution, with minor amounts of $FeAl_2O_4$ and $MgAl_2O_4$. On Earth chromite usually contains larger amounts of $MgAl_2O_4$ (spinel), with lesser amounts of $FeFe_2O_4$ (magnetite). Therefore, the density of the lunar chromites was judged to be about 5.0 gm/cm^3 vs. 4.5 gm/cm^3 for the terrestrial chromites. Lunar and terrestrial ilmenites have similar densities.

The thermal regime in which the magma chambers is located can be an important control on settling velocity. If there are sufficient vertical thermal gradients in the melt, classical upward and downward convection will be active. However, the lunar environment is one void of atmosphere (10^{-10} atm) and water. An important effect is that the lunar rocks are considerably less efficient in heat conduction. Therefore, a lunar magma will have better thermal insulation from heat loss than its terrestrial analog. Thus, temperature gradients and subsequent convection should be less. All other factors being equal, the net result is that crystal settling should be more effective on the Moon than on the Earth.

SUMMARY OF RESULTS

1. The viscosities of lunar basaltic melts (9.26 to 36.0 poises) are significantly less than those of terrestrial melts (260.2 to 1200 poises), a difference of 1-2 orders of magnitude.

2. The densities of lunar basaltic melts (2.89 to 3.34 g/cm^3) are greater than terrestrial magmas (2.65 to 2.8 g/cm^3), largely because of higher FeO and TiO_2, and lower Na_2O and K_2O contents for lunar magmas.

3. Viscosity of the silicate melt is the most important factor affecting the settling velocity. As shown in Fig. 1, differences in

TABLE 1. Chemical composition, density, and viscosity of lunar basalts.

	Apollo 11*		Apollo 12			Apollo 14	Apollo 15		Apollo 17
	Low K Avg (8)	High K Avg (6)	Ol Avg (9)	Pig Avg (4)	Ilm Avg (4)	VHA Avg (2)	Ol Avg (9)	Pig Avg (13)	Hi-Ti Avg (30)
SiO_2	40.67	40.37	44.32	46.46	44.47	45.80	44.98	47.98	38.84
TiO_2	10.18	11.77	2.65	3.35	4.63	1.89	2.41	1.82	12.35
Al_2O_3	10.40	8.84	8.03	10.38	9.76	13.20	8.81	9.46	8.84
FeO	18.68	19.28	21.11	19.72	20.78	17.70	22.37	20.13	18.94
MnO	0.27	0.24	0.28	0.27	0.27	0.24	0.30	0.28	0.27
MgO	6.92	7.56	14.07	7.94	8.52	9.70	10.42	8.74	8.52
CaO	11.70	10.59	8.61	11.03	10.78	10.30	9.79	10.54	10.80
Na_2O	0.41	0.52	0.22	0.28	0.32	0.51	0.28	0.31	0.32
K_2O	0.07	0.31	0.06	0.07	0.07	0.14	0.05	0.06	0.05
P_2O_5	0.09	0.17	0.08	0.11	0.10	—	0.08	0.07	0.06
S	0.16	0.22	0.06	0.07	0.08	—	0.07	0.06	0.17
Cr_2O_3	0.29	0.36	0.63	0.47	0.42	0.47	0.57	0.47	0.49
Total	99.84	100.23	100.12	100.15	100.20	99.95	100.13	99.92	99.65
Mg/Mg+Fe	0.40	0.41	0.54	0.42	0.42	0.49	0.45	0.44	0.44
Viscosity	25.62[†]	14.18	13.87	30.57	22.40	36.00	18.50	30.00	9.26
Density	3.22[‡]	3.29	3.00	2.96	3.04	2.89	2.99	2.91	3.34

*Apollo 14 composition from *Neal and Taylor* (1988); all others are from *Papike et al.* (1976).
† Viscosity units = poise = dyne-sec/cm^2.
‡ Density units = gm/cm^3.

TABLE 2. Chemical composition, density, and viscosity of terrestrial basalts.

	Basanite*	Olivine Basalt	Stillwater Mafic Rock	Tholeiite
SiO_2	44.30	49.61	49.41	51.13
TiO_2	2.51	3.54	1.20	2.48
Al_2O_3	14.70	11.28	15.78	14.54
Fe_2O_3	3.94	2.13	2.11	3.51
FeO	7.50	10.11	10.25	10.19
MnO	0.16	0.18	0.20	0.47
MgO	8.54	7.67	7.36	3.81
CaO	10.19	9.66	10.88	9.50
Na_2O	3.55	2.37	2.19	2.71
K_2O	1.96	1.83	0.16	1.19
H_2O+	1.20	0.80	0.23	0.31
H_2O-	0.42	0.42	0.07	0.12
P_2O_5	0.74	0.52	0.11	1.03
CO_2	0.18	—	—	—
Total	99.89	100.12	99.95	100.99
Mg/Mg+Fe	0.64	0.55	0.54	0.37
Viscosity	260.19[†]	302.60	736.80	1200.00
Density	2.80[‡]	2.81	2.76	2.76

*Basanite and tholeiite compositions are from *McBirney* (1984); olivine basalt is from *BVSP* (1981); Stillwater mafic rock is from *Helz* (1985).
† Viscosity units = poise = dyne-sec/cm^2.
‡ Density units = gm/cm^3.

TABLE 3. Particle settling velocities (cm/sec) in basalt melts.

	Periodotite (3.42 g/cm^3)	Ilmenite (4.72 g/cm^3)	Chromite* (4.5-5.0 g/cm^3)
Earth			
Basanite	0.52	1.60	1.42
Olivine Basalt	0.44	1.37	1.21
Stillwater Basic Rock	0.19	0.58	0.51
Tholeiite	0.12	0.35	0.32
Moon			
Apollo 11			
Low K	0.28	2.08	2.47
High K	0.31	3.44	4.29
Apollo 12			
Ol Basalt	1.07	4.41	5.13
Pig Basalt	0.53	2.04	2.37
Ilm Basalt	0.60	2.67	3.11
Apollo 14			
VHA	0.52	1.80	2.08
Apollo 15			
Ol Basalt	0.82	3.31	3.85
Pig Basalt	0.60	2.14	2.48
Apollo 17			
Hi-Ti Basalt	0.31	5.30	6.37

* The densities of 4.5 and 5.0 gm/cm^3 were used for terrestrial and lunar chromites, respectively.

densities between the various terrestrial basaltic melts are small (i.e., 0.15 gm/cm^3), such that a best-fit linear relationship of viscosity and velocity is possible. The data are more scatttered for the lunar estimates.

4. When the difference between the densities of the melt and particle is small, the density becomes a major factor affecting the settling velocity. For example, the densities of the Apollo 11 and 17 high-Ti basalts are >3.2 gm/cm^3 (3.22 and 3.34 gm/cm^3, respectively), and the density contrasts between these melts and the peridotite particle is down to 0.08 gm/cm^3. In this case, the settling velocities are low, even lower than those for terrestrial basanite and olivine basalt. These are the three symbols in the lower left of Fig. 1. Magma density has little effect on settling velocities for lunar ilmenite and chromite.

It is interesting to speculate upon the fate of olivine crystallizing from a high-Ti basaltic melt. With a density of about 3.1 gm/cm^3, it is entirely probable that olivine should float within a lunar high-Ti magma.

5. *Hess* (1960) considered 30,000 and 300 poises to be the upper and lower viscosity limits for the Stillwater magma. These same values were also used by *Wager and Brown* (1967) as the viscosity for the Stillwater complex (737 poises) near this lower

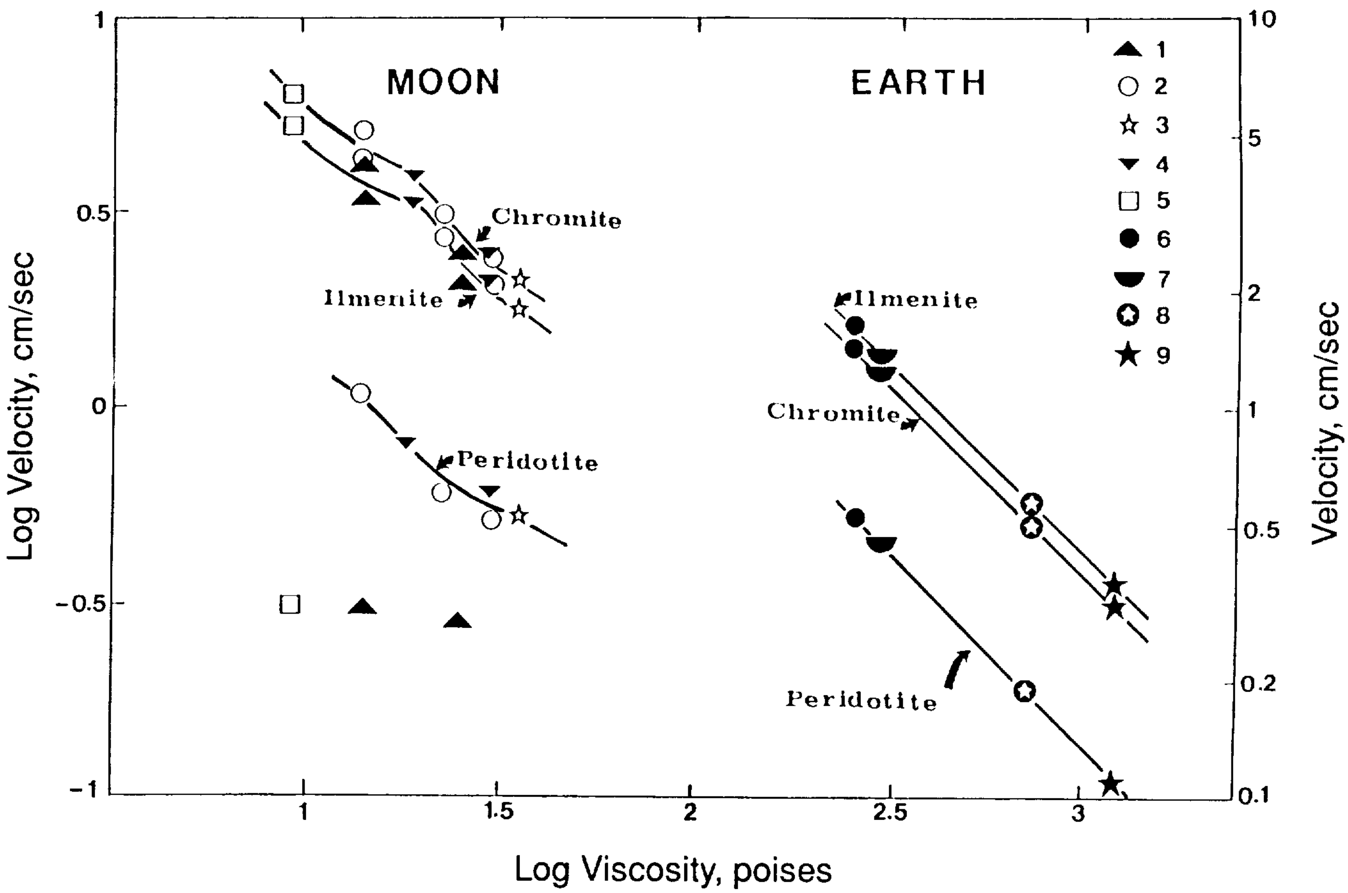


Fig. 1. Calculated viscosities vs. particle settling velocities for chromite, ilmenite, and peridotite in silicate basaltic melts on the Moon and the Earth. See the text for discussion of conditions. *Symbol notation:* 1. Apollo 11; 2. Apollo 12; 3. Apollo 14; 4. Apollo 15; 5. Apollo 17; 6. Basanite; 7. Olivine Basalt; 8. Stillwater Basic Rock; 9. Tholeiite. References: 1-5 from *Papike et al.* (1976); 6 and 9 from *McBirney* (1984); 7 from *BVSP* (1981); 8 from *Helz* (1985).

limit (Table 2). We suggest that this value of 300 poises is a lower limit for most terrestrial basaltic magmas. In contrast, the upper viscosity found on the Moon is still <36 poises. However, the densities of the terrestrial and most lunar basaltic magmas are within the range of 2.7-3.0 gm/cm^3.

6. In general, the particle settling velocities for oxide minerals on the Moon are greater by 5-10 times than those on Earth.

CONCLUSIONS

We conclude that oxide crystals will have greater settling velocities in lunar magmas than in terrestrial magmas. It is highly probable that stratiform ore deposits similar to or even larger than those on Earth exist on the Moon. The most likely ore minerals occurring in lunar intrusive bodies are chromite, ilmenite, and native FeNi metal.

On Earth, magmas from as deep as 200 km bring xenoliths to the surface because of their buoyancy ability, a direct function of melt viscosity. The greater settling velocity of peridotite in lunar melts indicates that the buoyancy effect of the melt is less. Therefore, the probability of finding upper mantle/lower crustal xenoliths brought to the surface of the Moon by deep-seated volcanism is less than on Earth.

Acknowledgments. We wish to thank E. N. Cameron for helpful discussions about stratiform deposits, particularly the Bushveld. Helpful comments by T. Labotka, C. Neal, and J. Taylor are also appreciated. The revised manuscript has benefited significantly from the incisive reviews by G. Ryder and P. Spudis. The study reported in this paper was supported in part by NASA Grant NAG 9-62 to L.A.T.

REFERENCES

Bottinga Y. and Weill D. F. (1970) Density of liquid silicate systems calculated from partial molar volumes of oxide compositions. *Am. J. Sci., 269,* 169-182.

Bottinga Y. and Weill D. F. (1972) The viscosity of magmatic silicate liquids: A model for calculation. *Am. J. Sci., 272,* 438-475.

BVSP (Basaltic Volcanism Study Project) (1981) *Basaltic Volcanism on the Terrestrial Planets.* Pergamon, New York. 1273 pp.

Helz R. T. (1985) Composition of fine-grained mafic rocks from sills and dikes associated with the Stillwater Complex. *Mont. Bur. Mines Geol., Spec. Publ., 92,* 97-117.

Hess H. H. (1960) Stillwater Igneous Complex, Montana. *Geol. Soc. Am. Mem.,* 80.

McBirney A. R. (1984) *Igneous Petrology.* Freeman, Cooper, New York. 504 pp.

Neal C. R. and Taylor L. A. (1988) Apollo 14 mare basalt petrogenesis: Assimilation of KREEP-like components by a fractionating magma. *Proc. Lunar Planet. Sci. Conf. 18th*, pp. 139-153.

Papike J. J., Hodges F. N., and Bence A. E. (1976) Mare basalts: Crystal chemistry, mineralogy, and petrology. *Rev. Geophys. Space Phys.*, *14*, 457-539.

Schultz P. H. (1976) Floor-fractured lunar craters. *Moon*, *15*, 241-273.

Wager L. R. and Brown G. M. (1967) *Layered Igneous Rocks*. Freeman, San Francisco.

N93-13975

APPLICATIONS FOR SPECIAL-PURPOSE MINERALS AT A LUNAR BASE

Douglas W. Ming

Solar System Exploration Division
Mail Code SN14
NASA Johnson Space Center
Houston TX 77058

Maintaining a colony on the Moon will require the use of lunar resources to reduce the number of launches necessary to transport goods from the Earth. It may be possible to alter lunar materials to produce minerals or other materials that can be used for applications in life support systems at a lunar base. For example, mild hydrothermal alteration of lunar basaltic glasses can produce special-purpose minerals (e.g., zeolites, smectites, and tobermorites) that in turn may be used in life support, construction, waste renovation, and chemical processes. A variety of zeolites, smectites, feldspars, feldspathoids, and tobermorites have been synthesized by mild hydrothermal alterations of synthetic basaltic glasses with chemical compositions similar to lunar basaltic glasses. Zeolites, smectites, and tobermorites have a number of potential applications at a lunar base. Zeolites are hydrated aluminosilicates of alkali and alkaline earth cations that possess infinite, three-dimensional crystal structures. They are further characterized by an ability to hydrate and dehydrate reversibly and to exchange some of their constituent cations, both without major change of structure. Based on their unique adsorption, cation exchange, molecular sieving, and catalytic properties, zeolites may be used as a solid support medium for the growth of plants, as an adsorption medium for separation of various gases (e.g., N_2 from O_2), as catalysts, as molecular sieves, and as a cation exchanger in sewage-effluent treatment, in radioactive waste disposal, and in pollution control. There are other possible applications for zeolites at lunar or other planetary bases, but they are too numerous to report here. Smectites are crystalline, hydrated 2:1 layered aluminosilicates that also have the ability to exchange some of their constituent cations. Like zeolites, smectites may be used as an adsorption medium for waste renovation, as adsorption sites for important essential plant growth cations in solid support plant growth mediums (i.e., "soils"), as cation exchangers, and in other important applications. However, the potential use of smectites at a lunar base may be less favorable than the use of zeolites, because zeolites have up to five times more capacity to exchange cations than smectites. Tobermorites are crystalline, hydrated single-chained layered silicates that have cation-exchange and selectivity properties between those of smectites and most zeolites. Tobermorites may be used as a cement in building lunar base structures, as catalysts, as media for nuclear and hazardous waste disposal, as exchange media for waste-water treatment, and in other potential applications. Special-purpose minerals synthesized at a lunar base may also have important applications at a space station and for other planetary missions. For example, zeolites or tobermorites might be used in waste renovation on the space station, or wastes may be sent to the lunar surface and processed at a lunar base that uses these special-purpose minerals for waste recycling. New technologies will be required at a lunar base to develop life support systems that are self-sufficient, and the use of special-purpose minerals may help achieve this self-sufficiency.

INTRODUCTION

The human exploration of our solar system is rapidly approaching as space agencies in the U.S., the U.S.S.R., Japan, China, and Europe are in the planning stages of advanced planetary missions. The first step in establishing a permanent human colony away from Earth may be the shortest: to the Moon. A number of reasons to colonize the Moon have been suggested, including scientific research, exploitation of lunar resources for use in building a space infrastructure, and attainment of self-sufficiency in the lunar environment as a first step in planetary exploration (*Duke et al.*, 1985). The close proximity of the Moon to the Earth also makes a lunar base attractive over other potential planetary bases. The lunar environment is one of the most barren environments for human existence when comparing our near neighbors in the solar system (e.g., Mars). Thus, the development of self-sufficient colonies on the Moon will greatly enhance the probability of the survival of a human colony on a more distant planetary body.

A self-sufficient lunar colony will require the use of lunar resources. Common constituents of the lunar regolith are silicate minerals (e.g., pyroxenes, olivines, feldspars), iron-titanium oxides (e.g., ilmenite), glass materials, and agglutinates (complex mixtures of glass and mineral fragments). The lunar regolith lacks ion-exchange minerals such as clay minerals (e.g., smectites) and zeolites. Components of the lunar regolith in their present state will probably not have very many applications, except to be used as shielding from solar radiation. It is likely that lunar materials (e.g., glass) will be altered to produce minerals and other materials with ion-exchange behaviors that can be used for applications in life support systems. These reactive minerals that may have potential uses at a lunar base have been called "special-purpose minerals" in this paper.

SPECIAL-PURPOSE MINERALS

Three major groups of minerals may be of interest to scientists and engineers as they design lunar base structures and life support systems. These special-purpose minerals are (1) zeolites,

TABLE 1. Representative unit-cell formulae and selected physical and chemical properties of important special-purpose minerals.

Special-Purpose Minerals	Representative Unit-Cell Formula*	Void Volume (%)	Cation Exchange Capacity meq/100 g
Zeolites			
Analcime	$Na_{16}\{Al_{16}Si_{32}O_{96}\}\cdot16H_2O$	18	460
Chabazite	$(Na_2,Ca)_6\{Al_{12}Si_{24}O_{72}\}\cdot40H_2O$	47	420
Clinoptilolite	$(Na_3,K_3)\{Al_6Si_{30}O_{72}\}\cdot24H_2O$	34	220
Mordenite	$Na_8\{Al_8Si_{40}O_{96}\}\cdot24H_2O$	28	220
Phillipsite	$(Na,K)_5\{Al_5Si_{11}O_{32}\}\cdot20H_2O$	31	380
Linde Type A	$Na_{96}\{Al_{96}Si_{96}O_{384}\}\cdot216H_2O$	47	540
Linde Type X	$Na_{86}\{Al_{86}Si_{106}O_{384}\}\cdot264H_2O$	50	470
Phyllosilicates			
Vermiculite	$(Mg,Fe)_3(Al_{0.4}Si_{3.6})O_{10}(OH)_2\cdot nH_2OMg_{0.8}$	—	160‡
Smectite†	$(Al_{1.5}Mg_{0.5})Si_4O_{10}(OH)_2\cdot nH_2OCa_{0.25}$	—	110‡
Tobermorites			
Tobermorite	$Ca_5Si_6H_2O_{18}\cdot4H_2O$	—	<15
Al-Substituted Tobermorite	$Ca_5(Al,Si)_6O_{18}\cdot nH_2ONa_x$	—	182§

* Taken mainly from *Breck* (1974).
† Montmorillonite.
‡ *Alexaides and Jackson* (1965).
§ *Komarneni and Roy* (1983).

(2) phyllosilicates, and (3) tobermorites. Several natural and synthetic minerals of these groups along with representative unit cell formulae are listed in Table 1.

Zeolites

Zeolites were discovered in 1756 by the Swedish mineralogist Cronstedt who named them from the Greek words *zein* and *lithos*, meaning "boiling stones." Since that time there have been about 50 natural zeolites discovered, and several hundred synthetic species have been made in the laboratory. Zeolites are hydrated aluminosilicates of alkali and alkaline Earth cations (e.g., K^+, Na^+, Ca^{2+}, Mg^{2+}) that possess infinite three-dimensional crystal structures (i.e., tektosilicates).

The primary building units of the zeolite crystal structure are $(Al,Si)O_4$ tetrahedra. When Al^{3+} and sometimes Fe^{3+} substitute for Si^{4+} in the central cation position of the tetrahedron, a net negative charge is generated. This negative charge is counterbalanced primarily by alkali and alkaline Earth cations (generally called "exchange cations"). The exchange cations are loosely held near the seat of charge within the zeolite structure and can be replaced by other cations in solution. Natural zeolites may have measured cation exchange capacities (CEC) of 200-300 meq/100 g, whereas synthetic zeolites may have a CEC as high as 500-600 meq/100 g.

Zeolites may have void volumes within their structures of up to 50% when dehydrated. Because of these large void volumes, zeolites are able to hydrate, dehydrate, and adsorb a wide variety of molecules without causing any changes to their crystal structure. Zeolites also have unique molecular sieving and catalytic properties. The occurrence, structures, and properties of natural zeolites have been presented by *Mumpton* (1981), *Sand and Mumpton* (1978), *Gottardi and Galli* (1985), and *Ming and Mumpton* (1989). Structures and properties of synthetic zeolites are described by *Breck* (1974).

Phyllosilicates

The term phyllosilicate was derived from the Greek word *phyllon*, which means "leaf," because most of the minerals in this group have a platy or flaky habit. Most of the members of this class of aluminosilicates consist either of 2:1 layered minerals (i.e., 1 tetrahedral sheet : 1 octahedral sheet : 1 tetrahedral sheet) or 1:1 layered minerals (i.e., 1 tetrahedral sheet : 1 octahedral sheet).

Because of their cation-exchange behavior, smectites and vermiculites should be of interest to scientists concerned with applications of phyllosilicates at a lunar base. Smectites and vermiculites are 2:1 layered minerals that have a net negative charge generated by isomorphic substitutions in their 2:1 layers. The negative charge is counterbalanced by hydrated cations located in the interlayer between the 2:1 layers. Smectites and vermiculites, like zeolites, have the capability of exchanging some of their constituent cations with cations from solution; however, the structure in 2:1 layered minerals is not as rigid as the zeolite structure. Generally, smectites will expand in the interlayer depending on the molecule type and on the hydration of the system, whereas vermiculites somewhat restrict interlayer expansion. Vermiculites are higher charge materials (e.g., 140-160 meq/100 g) than smectites (e.g., 80-105 meq/100 g).

The occurrence, structures, and properties of phyllosilicates are described in *Grim* (1968), *Brindley and Brown* (1980), and *Dixon and Weed* (1989).

Tobermorites

Tobermorite, a rare hydrous silicate mineral, was discovered by Heddle in 1880. The crystal structures of tobermorites are not well known. It is known, however, that they have a layered structure similar to 2:1 phyllosilicates. A distorted, central calcium oxide octahedral sheet is flanked on both sides by single chains of silicate tetrahedra. Anomalous tobermorites have numerous Si-

O-Si bridges between adjacent silicate chains in the interlayer, whereas normal tobermorites only have a few Si-O-Si bridges in the interlayer. These Si-O-Si bridges form "interlayer" bridges that are similar to the tunnels in zeolites (*Komarneni and Guggenheim,* 1988). In synthetic systems, it is possible to substitute Al^{3+} or Fe^{3+} for Si^{4+} in the central tetrahedral cation site. As in zeolites, a net negative charge is generated in these Al- or Fe-substituted tobermorites. The negative charge is counterbalanced by various cations (e.g., Na^+, Ca^{2+}, Cs^+), and it is therefore possible to exchange cations on these sites with cations in solution. *Komarneni et al.* (1987) have shown that Al-substituted synthetic tobermorites are selective for Cs^+ over Na^+ and Ca^{2+} on the exchange sites. The CECs of synthetic tobermorites depend on the degree of Al- and Fe-substitution for Si. *Komarneni and Roy* (1983) found that Al-substituted synthetic tobermorites had CECs as high as 182 meq/100 g.

The hydration/dehydration properties of tobermorite are somewhat different from 2:1 phyllosilicates and zeolites. Unlike smectites, dehydrated normal tobermorites collapse and then do not rehydrate (*El-Hemaly et al.,* 1977). However, anomalous tobermorites, which have numerous Si-O-Si bridges in the interlayer, do not collapse when dehydrated because the bridges keep them open.

The structures and properties of tobermorites are described in *Taylor* (1964), *Komarneni and Roy* (1983), and *El-Hemaly et al.* (1977).

SYNTHESIS OF SPECIAL-PURPOSE MINERALS

Special-purpose minerals do not exist in the lunar regolith due to the lack of water, which is necessary to form these minerals. However, zeolites, smectites, and tobermorites have been synthesized under mild hydrothermal conditions from synthetic basaltic glass with chemical compositions similar to lunar basaltic glasses (*Ming and Lofgren,* 1990). Basaltic glass is abundant in many lunar "soils" (*Williams and Jadwick,* 1980); therefore, it is probable that special-purpose minerals can be easily synthesized from lunar regolith.

A number of zeolites and other mineral phases have been synthesized from terrestrial basaltic glasses. For example, *Höller and Wirsching* (1978) have hydrothermally altered terrestrial basaltic glass with H_2O and NaOH solutions to form the zeolites chabazite, phillipsite, and analcime. In another study (*Wirsching,* 1981), basaltic glass altered with $CaCl_2$ solutions formed several zeolites (phillipsite, scolecite, wairakite, and levynite) and minor amounts of montmorillonite.

The hydrothermal synthesis of zeolite molecular sieves from reagent-grade chemicals has been commonplace in industry over the past 30 years. The production of chemically pure oxides and other chemical reagents from lunar materials may be necessary for industrial uses on the Moon. Hence, the synthesis of zeolites and other minerals from chemical reagents should not be a problem. A comprehensive review of zeolite synthesis is found in *Barrer* (1982).

The major resource necessary for the synthesis of special-purpose minerals that will be lacking on the lunar surface is water. Water will have to be transported to the Moon from the Earth, or will have to be made on the lunar surface from regolith oxygen (*Williams,* 1985; *Gibson and Knudsen,* 1985; *Cutler and Krag,* 1985) and solar wind implanted hydrogen (*Carter,* 1985; *Tucker et al.,* 1985; *Blanford et al.,* 1985). Power requirements to heat the samples should be small. In fact, the month-long lunar day at the equatorial region may reach temperatures as high as 120°C. Temperatures around 120°C may be high enough to form special-purpose minerals by altering the glass material from the regolith under mild hydrothermal conditions.

APPLICATIONS OF SPECIAL-PURPOSE MINERALS

Because of their unique cation-exchange, adsorption, hydration-dehydration, and catalytic properties, special-purpose minerals are being used in a wide variety of industrial and agricultural processes, although the use of these minerals for agricultural applications is in its infancy. Basic research is just now supplying the necessary information on the various properties that make these reactive minerals attractive for agricultural purposes. As our knowledge on the properties of special-purpose minerals grows, not only will their use in terrestrial processes increase, but their possible uses at planetary bases will become more evident.

Zeolites

The zeolite group of minerals may be the most attractive of the special-purpose minerals for use at a lunar base. Zeolites are some of the most effective cation exchangers known and they are relatively easy to synthesize at low temperatures and pressures. The use of zeolites may be most advantageous in controlled ecological life support systems (CELSS).

Zeoponics. Zeoponics is only in its developmental stages and is defined as the cultivation of plants in zeolite substrates that (1) contain essential plant growth cations on their exchange sites and (2) have minor amounts of mineral phases (e.g., apatite) or anion exchange resins (e.g., activated aluminum) that supply essential plant growth anions (e.g., $H_2PO_4^{2-}$) (*Ming,* 1989). A zeoponics system is illustrated in Fig. 1.

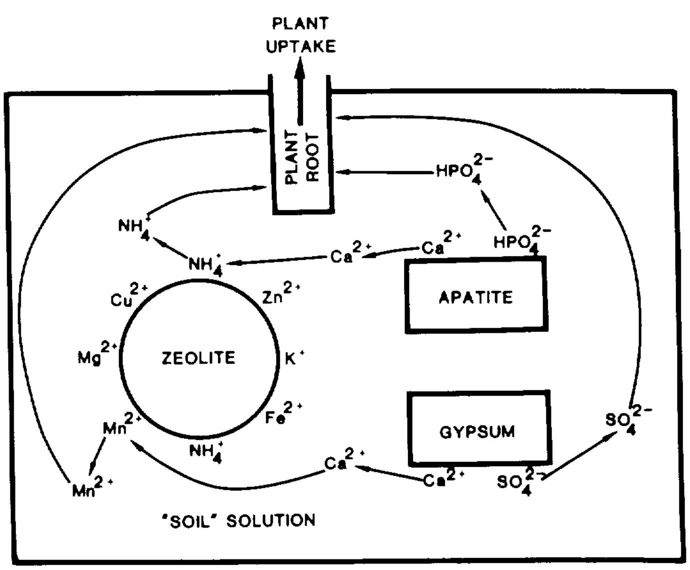


Fig. 1. Zeoponic system for plant growth. Apatite and gypsum undergo dissolution at their surfaces, releasing Ca^{2+}, HPO_4^{2-}, and SO_4^{2-} into solution. The Ca^{2+} competes with and replaces cations on zeolitic exchange sites, releasing plant-essential cations into solution for plant uptake. The HPO_4^{2-} and SO_4^{2-} also are available for plant uptake.

The use of zeolites as amendments to soils to increase plant fertility is not a new idea (see *Ming*, 1989); however, little has been done using zeolites as a substrate by themselves. The high CEC of zeolites will aid in holding essential plant growth cations until the plant requires these nutrients. Although little information is available, *Stoilov and Popov* (1982) reported the use of clinoptilolite (a highly siliceous zeolite) as a raw material for plant substrates. The zeolitic substrate was found to act as a reservoir for nutrient cations, to have desirable strength and other physical properties, to be sterile with respect to pathogenic microorganisms, and to be aesthetically pleasing. Depending on the plant variety, 20-150% increases in yields over control plots were observed for tomatoes, strawberries, peppers, and rice. Also, the ripening of rice, cotton, and tomatoes was accelerated in the zeolite substrate.

Zeoponics may rival hydroponics or aeroponics in plant production. Plants will be a key to sustaining a crew at a self-sufficient lunar base, and zeolites deserve further consideration as a substrate in which to grow plants.

Wastewater recycling. Water will be a precious commodity at a lunar base; therefore, it is essential that water be recycled. Zeolites have been used for cation-exchange resins in water purification for the past 50 years. For example, some zeolites are highly selective for ammonium ions and can be used to remove ammonium in secondary effluents from urban sewage (*Mercer et al.*, 1970; *Jorgensen et al.*, 1976; *Liberti et al.*, 1979). Of the various methods to remove NH_4^+ from terrestrial wastewaters (*Jorgensen et al.*, 1976), zeolites appear to be the best choice for use at a lunar base.

Zeolites should be able to remove cations other than NH_4^+, e.g., Cs^+, Rb^+, Sr^{2+}, Pb^+, Zn^{2+}, etc. from wastewaters at a lunar base. It should be possible to synthesize a specific zeolite that is highly selective for a given cation in lunar wastewaters. Once the zeolite exchange column has been spent (i.e., saturated), the column can be chemically regenerated and reused. A potential wastewater purification system at a lunar base is illustrated in Fig. 2.

Gas separation purification. Gas exchange in a CELSS will have to be rigidly monitored. Slight variations in gas mixtures may be detrimental to crew and plant life. Zeolites have void volumes of 20-50%, and dehydrated zeolite structures are effective sorbents of gases. Various zeolite species have the capability to remove specific gases (e.g., SO_2, CO_2, N_2, H_2S, H_2O) from gas streams. For example, natural chabazite and synthetic molecular-sieve zeolite NaX are used to remove CO_2 and H_2O from industrial gases (*Mumpton*, 1975; *Webber*, 1972). Once adsorbed on the zeolite, the gases can be removed by pressure-swing desorption cycles and reused for gas separation.

The flow diagram in Fig. 3 illustrates a potential lunar base gas separation process (after *Minato and Tamura*, 1978) for a system containing H_2O, O_2, N_2, and CO_2. First, water and CO_2 are removed from the gas stream by pretreatment columns containing zeolites (e.g., clinoptilolite) that are selective for dipolar gases. Next the air stream is fed into columns containing zeolites (e.g., zeolite Ca-A, mordenite, chabazite) that selectively adsorb quadrupolar N_2. Oxygen passes through the zeolite columns into an oxygen holding tank (*Stewart and Heck*, 1969). Nitrogen is removed from the zeolite column by a pressure-swing desorption process. The series of three pretreatment columns and zeolite columns allows continuous production of O_2 and N_2 by alternating between columns one, two, and three.

Other applications. Applications for zeolites at a lunar base are numerous. Because of their unique properties, they can be used as catalysts and adsorbents (e.g., *Boreskov and Minachev*, 1979; *Breck*, 1974; *Weisz*, 1980; *Rabo*, 1976). The use of zeolites for other terrestrial industrial and agricultural applications has been reviewed extensively elsewhere (e.g., see *Sand and Mumpton*, 1978; *Pond and Mumpton*, 1984; *Townsend*, 1980; *Murakami et al.*, 1986; *Drzaj et al.*, 1985).

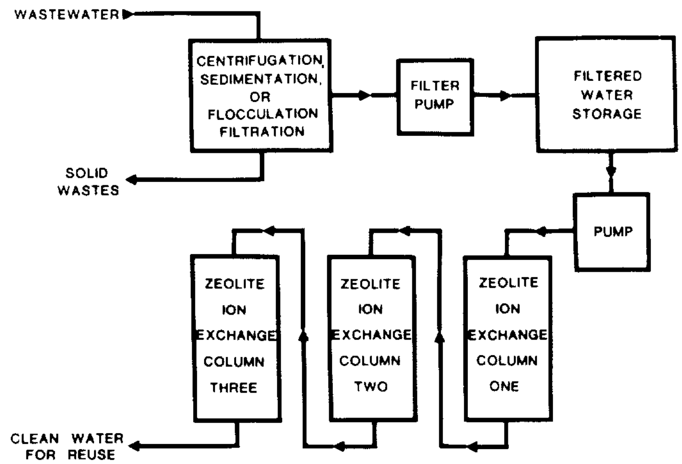


Fig. 2. Wastewater recycling system using zeolites to remove NH_4^+ and other undesirable cations.

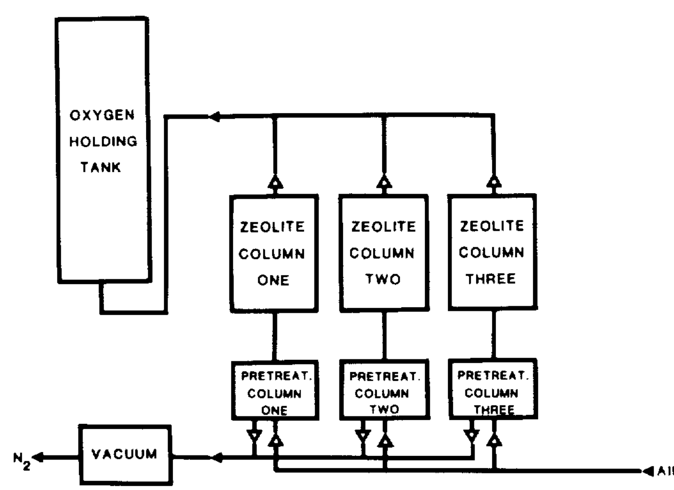


Fig. 3. Schematic diagram of a gas separation system for O_2, N_2, CO_2, and water (after *Minato and Tamura*, 1978).

Phyllosilicates

Smectites appear to be the most favorable phyllosilicate to use at a lunar base because of their cation-exchange properties. However, the potential use of smectites at a lunar base may be somewhat less favorable than the use of zeolites, which have up to five times more capacity to exchange cations than smectites. Nevertheless, smectites are responsible for a large portion of the CEC in terresrial soils (*Borchardt,* 1977). These smectitic cation exchange sites in soils create sites to hold fertilizer cations such as K^+, NH_4^+, Ca^{2+}, Mg^{2+}, Zn^{2+}, and Fe^{2+}. The addition of a CEC mineral to lunar soils in order to produce a soil for plant growth at a lunar base was one of the major recommendations from a NASA workshop entitled "Lunar soils for the growth of higher plants" (*Ming and Henninger,* 1989). Smectites appear to be one of the best minerals to add to lunar materials to produce a reactive and productive soil. Also, calcined smectite (i.e., aggregates of clay particles heated to high temperatures) forms hardened particles, and, when mixed with other components (e.g., quartz sand, soil, peat moss), makes a productive terrestrial root medium. The irregular shape of the particles creates large pores for aeration and drainage. Calcined smectites also have sizable CECs (e.g., as high as 25 meq/100 g), which results in good nutrient retention. A productive lunar soil may consist of calcined smectite combined with lunar materials (e.g., sand-sized feldspars).

Expanded vermiculites are widely used as potting media. Water between clay particles causes expansion when the particles are heated. The expanded volume can be up to 16 times larger than the original mineral. Expanded vermiculites are very desirable solid-support substrates for plant growth because of their nutrient and water retention, good aeration, and low bulk densities. Vermiculite solid-support media may act as excellent soils for plant growth on the Moon; however, it is fairly difficult to synthesize vermiculites. Vermiculites are generally formed by the accelerated weathering of micas as an extension of the natural process on Earth.

Phyllosilicates also can adsorb various gases and molecules on external and internal surfaces, but to a lesser extent than most zeolites. However, phyllosilicates, especially smectites, have important industrial applications as sorbents (*Barrer,* 1978). For example, amino acids are sorbed from aqueous solution by Na-, Ca-, and H-saturated smectites (*Greenland et al.,* 1962; *Talibudeen,* 1955). Also CO_2 and N_2 will adsorb on external surfaces of smectites (*Fripiat et al.,* 1974), and organic acids (e.g., humic and fulvic acids) may be adsorbed in the interlayers of smectites (*Mortland,* 1970). Smectites may perhaps be most useful in the removal of various organics from wastewaters at lunar bases.

Tobermorites

Tobermorite has been indentified as the principal binding agent in autoclaved cement products (*Kalousek,* 1955). Also, poorly crystalline tobermorite-like minerals (e.g., "ill-crystallized" tobermorites) are major phases in cement hydration (*Taylor,* 1964). Concrete has been suggested as a suitable structure to house facilities and personnel at a lunar base (*Lin,* 1985; *Young,* 1985). Lunar concrete structures are capable of withstanding the effects of temperatures, solar wind, radiation, cosmic rays, and micrometeorites (*Lin,* 1985). *Lin et al.* (1988) have also shown that actual lunar material works quite well as an aggregate for concrete. However, lunar raw materials have not been used to produce cement. Since tobermorite can be readily synthesized from lunar basaltic analog glass (*Ming and Lofgren,* 1990), it may be possible to use lunar basaltic glass as a cement precursor and heat (~160°C) the glass, solution, and aggregate under mild hydrothermal conditions to produce a concrete.

Aluminum- and Fe-substituted tobermorites also exhibit significant cation exchange capacities (*Komarneni et al.,* 1982, 1987; *Komarneni and Roy,* 1983; *Pannaparayil et al.,* 1985). Tobermorites are being investigated for their terrestrial applications in catalysis and in nuclear and hazardous waste disposal (*Komarneni and Roy,* 1983). Nuclear energy may play a major role in the development of lunar bases (*Buden and Angelo,* 1985; *French,* 1985). If nuclear energy is to be used as a power source on the Moon, it will be necessary to shield the reactor and provide for safe disposal or storage of nuclear wastes. Since tobermorites are highly selective for radioactive waste cations (e.g., $^{137}Cs^+$), concretes with tobermorites as the primary binding agent may act as substrates to trap and store radioactive cations.

WHY SPECIAL-PURPOSE MINERALS?

Organic ion exchangers (e.g., polystyrene divinylbenzene) are in widespread use in industry, along with zeolite ion exchangers. The production of organic ion exchange materials at a lunar base may be difficult because of the small quantities of organic compounds in the lunar regolith. Hence, the lack of organic molecules further supports the use of inorganic zeolites (and, possibly, tobermorites and smectites) as ion exchangers at lunar bases.

Zeolites, smectites, and tobermorites are relatively easy to synthesize from glass-starting materials. A wealth of information is available on zeolite synthesis; therefore, it should be fairly easy to produce zeolite (or tobermorite) species that will cater to particular needs.

Special-purpose minerals may have a wide variety of applications, from construction materials to plant growth substrates. The terrestrial use of special-purpose minerals is only in its infancy and, no doubt, as the science grows, the uses for special-purpose minerals at lunar bases will become more evident.

REFERENCES

Alexaides C. A. and Jackson M. L. (1965) Quantitative determination of vermiculite in soils. *Soil Sci. Soc. Am. Proc., 29,* 522-527.

Barrer R. M. (1978) *Zeolites and Clay Minerals as Sorbents and Molecular Sieves.* Academic, New York. 497 pp.

Barrer R. M. (1982) *Hydrothermal Chemistry of Zeolites.* Academic, London. 360 pp.

Blanford G. E., Borgesen P., Maurette M., Moller W., and Monart B. (1985) Hydrogren and water desorption on the Moon: Approximate, on-line simulations. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 603-609. Lunar and Planetary Institute, Houston.

Borchardt G. A. (1977) Montmorillonite and other smectite minerals. In *Minerals in Soil Environments* (J. B. Dixon and S. B. Weed, eds.), pp. 293-330. Soil Science Society of America, Madison.

Boreskov G. K. and Minachev Kh. M., eds. (1979) *Applications of Zeolites in Catalysis.* Akadémiai Kiadó, Budapest. 179 pp.

Breck D. W. (1974) *Zeolite Molecular Sieves.* Wiley, New York. 771 pp.

Brindley G. W. and Brown G. (1980) *Crystal Structures of Clay Minerals and Their X-ray Identification.* Mineralogical Society, London. 495 pp.

Buden D. and Angelo J. A. (1985) Nuclear energy—Key to lunar development. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 85-98. Lunar and Planetary Institute, Houston.

Carter J. L. (1985) Lunar regolith fines: A source of hydrogen. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 571-581. Lunar and Planetary Institute, Houston.

Cutler A. H. and Krag P. (1985) A carbothermal scheme for lunar oxygen production. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 559-569. Lunar and Planetary Institute, Houston.

Dixon J. B. and Weed S. B., eds. (1989) *Minerals in Soil Environments, 2nd edition.* Soil Science Society of America, Madison. 1244 pp.

Drzaj B., Hocevar S., and Pejovnik S. (1985) *Zeolites: Synthesis, Structure, Technology, and Applications.* Elsevier, New York. 690 pp.

Duke M. B., Mendell W. W., and Roberts B. B. (1985) Strategies for a permanent lunar base. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 57-68. Lunar and Planetary Institute, Houston.

El-Hemaly S. A. S., Mitsuda T., and Taylor H. F. W. (1977) Synthesis of normal and anomalous tobermorites. *Cem. Concr. Res.,* 7, 429-438.

French J. R. (1985) Nuclear powerplants for lunar bases. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 99-106. Lunar and Planetary Institute, Houston.

Fripiat J. J., Cruz M. I., Bohor B. F., and Thomas J. (1974) Interlamellar adsorption of carbon dioxide by smectites. *Clays Clay Miner., 22,* 23-30.

Gibson M. A. and Knudsen C. W. (1985) Lunar oxygen production from ilmenite. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 543-550. Lunar and Planetary Institute, Houston.

Gottardi G. and Galli E. (1985) *Natural Zeolites.* Springer-Verlag, New York. 409 pp.

Greenland D. J., Laby R. H., and Quirk J. P. (1962) Adsorption of glycine and its di-, tri-, and tetra-peptides by montmorillonite. *Trans. Faraday Soc., 58,* 829-841.

Grim R. E. (1968) *Clay Mineralogy.* McGraw-Hill, New York. 596 pp.

Höller H. and Wirsching U. (1978) Experiments on the formation of zeolites by hydrothermal alteration of volcanic glasses. In *Natural Zeolites: Occurrence, Properties, Use* (L. B. Sand and F. A. Mumpton, eds.), pp. 329-336. Pergamon, New York.

Jorgensen S. E., Libor O., Lea Graber K., and Barkacs K. (1976) Ammonia removal by use of clinoptilolite. *Water Res., 10,* 213-224.

Kalousek G. L. (1955) Tobermorite and related phases in the system CaO-SiO_2-H_2O. *J. Am. Concr. Inst., 26,* 989-1011.

Komarneni S. and Guggenheim S. (1988) Comparison of cation exchange in ganophyllite and [Na+Al]-substituted tobermorite: Crystal-chemical implications. *Mineral. Mag., 52,* 371-375.

Komarneni S. and Roy D. M. (1983) Tobermorites: A new family of cation exchangers. *Science, 221,* 647-648.

Komarneni S., Roy D. M., and Roy R. (1982) Al-substituted tobermorite: Shows cation exchange. *Cem. Concr. Res., 12,* 773-780.

Komarneni S., Breval W., Miyake M., and Roy R. (1987) Cation-exchange properties of (Al+Na)-substituted synthetic tobermorites. *Clays Clay Miner., 35,* 385-390.

Liberti L., Boari G., and Passino R. (1979) Phosphates and ammonia recovery from secondary effluents by selective ion exchange with production of a slow-release fertilizer. *Water Res., 13,* 65-73.

Lin T. D. (1985) Concrete for lunar construction. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 381-390. Lunar and Planetary Institute, Houston.

Lin T. D., Love H., and Stark D. (1988) Physical properties of concrete made with Apollo 16 lunar soil sample (abstract). In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century,* p. 159. Lunar and Planetary Institute, Houston.

Mercer B. W., Ames L. L., Touhill C. J., Van Slyke W. J., and Dean R. B. (1970) Ammonia removal from secondary effluents by selective ion exchange. *J. Water Pollut. Control. Fed., 42,* R95-R107.

Minato H. and Tamura T. (1978) Production of oxygen and nitrogen with natural zeolites. In *Natural Zeolites: Occurrence, Properties, Use* (L. B. Sand and F. A. Mumpton, eds.), pp. 509-516. Pergamon, New York.

Ming D. W. (1989) Manufactured soils at planetary bases for the growth of plants. In *Lunar Base Agriculture: Soils for Plant Growth* (D. W. Ming and D. L. Henninger, eds.), pp 93-105. American Society of Agronomy, Madison.

Ming D. W. and Henninger D. L. (1989) *Lunar Base Agriculture: Soils for Plant Growth.* American Society of Agronomy, Madison. 255 pp.

Ming D. W and Lofgren G. E. (1990) Crystal morphologies of minerals formed by hydrothermal alteration of synthetic lunar basaltic glass. In *Soil Micromorphology: A Basic and Applied Science* (L. A. Douglas, ed.), pp. 463-470. Elsevier, Amsterdam.

Ming D. W. and Mumpton F. A. (1989) Zeolites in soils. In *Minerals in Soil Environments,* 2nd edition (J. B. Dixon and S. B. Weed, eds.), pp. 873-911. Soil Science Society of America, Madison.

Mortland M. M. (1970) Clay organic complexes and interactions. *Adv. Agron.,* 22, 75-117.

Mumpton F. A. (1975) Commercial utilization of natural zeolites. In *Industrial Minerals and Rocks, 4th edition* (S. J. Lefond, ed.), pp. 1262-1274. Amer. Inst. Mining Metall. Petrol. Engrs. Inc., New York.

Mumpton F. A., ed. (1981) *Mineralogy and Geology of Natural Zeolites.* Reviews in Mineralogy, Vol. 4, Mineralogical Society of America, Washington, DC. 225 pp.

Murakami Y., Iijima A., and Ward J. W., eds. (1986) *New Developments in Zeolite Science and Technology.* Elsevier, New York. 1091 pp.

Pannaparayil T., Komarneni S., Breval E., Roy D. M., and Mulay L. N. (1985) Fe^{3+}-substituted tobermorites: Synthesis and characterization by Mossbauer spectroscopy and other techniques. *Mater. Res. Bull., 20,* 1393-1400.

Pond W. G. and Mumpton F. A., eds. (1984) *Zeo-Agriculture: Use of Natural Zeolites in Agriculture and Aquaculture.* Westview, Boulder. 296 pp.

Rabo J. A., ed. (1976) *Zeolite Chemistry and Catalysis.* American Chemical Society Monograph No. 171., Washington, DC. 796 pp.

Sand L. B. and Mumpton F. A., eds. (1978) *Natural Zeolites: Occurrence, Properties, Use.* Pergamon, New York. 546 pp.

Stewart H. A. and Heck J. L. (1969) Pressure swing adsorption. *Chem. Eng. Prog., 65,* 78-83.

Stoilov G. and Popov N. (1982) Agricultural uses of natural zeolites in Bulgaria (abstract). In *Zeo-Agriculture '82: A Conference on the Use of Natural Zeolites in Agricultural and Aquaculture.* p. 38. International Committee on Natural Zeolites, Rochester, New York.

Talibudeen O. (1955) Complex formation between montmorilonoid clays and amino-acids and proteins. *Trans. Faraday Soc., 51,* 582-590.

Taylor H. F. W. (1964) The calcium silicate hydrates. In *The Chemistry of Cements* (H. F. W. Taylor, ed.), pp. 167-232. Academic, New York.

Townsend R. P., ed. (1980) *The Properties and Applications of Zeolites.* The Chemical Society, Burlington House, London. 430 pp.

Tucker D. S., Vaniman D. T., Anderson J. L., Clinard F. W., Feber R. C., Frost H. M., Meek T. T., and Wallace T. C. (1985) Hydrogen recovery from extraterrestrial materials using microwave energy. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 583-590. Lunar and Planetary Institute, Houston,

Webber D. A. (1972) Adsorptive removal of carbon dioxide from air at intermediate low temperatures. *Chem. Eng. (London), 257,* 18-23.

Weisz P. B. (1980) Molecular shape selective catalysis. *Pure Appl. Chem., 52,* 2901-2103.

Williams R. J. (1985) Oxygen extraction from lunar materials: An experimental test of an ilmenite reduction process. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 551-558. Lunar and Planetary Institute, Houston.

Williams R. J. and Jadwick J. J., eds. (1980) *Handbook of Lunar Materials.* NASA RP-1057, Washington, DC. 120 pp.

Wirsching U. (1981) Experiments on the hydrothermal formation of calcium zeolites. *Clays Clay Miner., 29,* 171-183.

Young J. F. (1985) Concrete and other cement-based composites for lunar base construction. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 391-397. Lunar and Planetary Institute, Houston.

WATER AND CHEESE FROM THE LUNAR DESERT: ABUNDANCES AND ACCESSIBILITY OF H, C, AND N ON THE MOON

N92-17976

L. A. Haskin

Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences
Washington University
St. Louis MO 63130

The Moon has been underrated as a source of H, N, C, and other elements essential to support life and to provide fuel for rockets. There is enough of these elements in each cubic meter of typical lunar soil to provide a substantial lunch for two, if converted to edible forms. The average amount of C per square meter of the lunar surface to a depth of 2 m is some 35% of the average amount per square meter tied up in living organisms on Earth. The water equivalent of H in the upper 2 m of the regolith averages at least 1.3 million liters per square kilometer. Mining of H from a small fraction of the regolith would provide all the rocket fuel needed for thousands of years. These elements can be removed from the soil by heating it to high temperature. Some favor the unproven resources of Phobos, Deimos, or near-Earth asteroids instead of the Moon as a source of extraterrestrial material for use in space, or Mars over the Moon as a site for habitation, partly on the basis that the chemical elements needed for life support and propellant are readily abundant on those bodies but not on the Moon. Well, the Moon is not as barren of H, C, and N as is commonly perceived. In fact, the elements needed for life support and for rocket fuel are plentiful there, although the ore grades are low. Furthermore, the proximity of the Moon and consequent lower cost of transportation and shorter trip and communication times favor that body as the logical site for early acquisition of resources and extraterrestrial living.

ABUNDANCES OF H, C, N, P, S, AND NOBLE GASES

By Earth's standards, the Moon is very dry; no free-standing water ice has been found on it and hydrous minerals are essentially absent from the acquired lunar samples. That does not mean that water is inaccessible there, however. There may be water of cometary or meteoritic origin trapped in the cold regolith of permanently shaded crater floors at the poles (*Arnold,* 1979; see also *Lanzerotti and Brown,* 1981, for arguments against), but we ignore that possible source in this analysis. We consider not how much water is present, but how abundant the elemental constituents of water are. One constituent, O, is the most abundant element on the Moon; some 44% of the mass of lunar surface rocks and soils is O. The other constituent, H, is so scarce in the lunar interior that we cannot claim to have measured any indigenous H in samples of mare basalts. Nevertheless, thanks to implantation of ions from the solar wind into the grains of lunar soil, there is enough H in a typical cubic meter of the lunar regolith to yield more than a pint and a half of water ($\approx$0.7 l). Despite consideration of this resource by others (e.g., *McKay and Williams,* 1979; *Bustin et al.,* 1984; *Carter,* 1984; *Gibson et al.,* 1988), the availability of H seems not to be generally recognized.

The concentration of H in typical lunar soil is $\approx$50 μg/g (e.g., *DesMarais et al.,* 1974, mean for 18 soils 59 ± 16 μg/g; *Bustin et al.,* 1984, mean for 15 soils 50 ± 23μg/g), for a total of $\approx$100 g/m^3 (the density of lunar soil is $\approx$1.75 g cm^3). Based on the soils sampled in the deep drill strings of the Apollos 15, 16, and 17 missions, these concentrations hold to a depth of 2 m and probably more. At 50 μg/g of H, this corresponds to >1.5 million liters of H_2O per square kilometer to a depth of 2 m or one million gallons per square mile to a depth of 2 yd. There are some 3.8×10^{13} m^3 of regolith per meter of depth at the lunar surface and, thus, some 7.6×10^9 tonnes of H in the outer 2 m of the Moon. To put this into perspective, this corresponds to about 6.8×10^{10} tonnes of water, or the amount in a lake of dimensions 10 km wide × 68 km long × 100 m deep. Since we do not know the average depth of regolith with this concentration, and since some soils may contain as much as 100 μg/g H, this is a conservative estimate. The problem is not that H is scarce on the Moon, but whether it is economically accessible.

Along with this $\approx$100 g per m^3 of H are $\approx$100 g of N, $\approx$200 g of C, $\approx$1.8 kg S, $\approx$1 kg of P, and noble gases ($\approx$20 g of He, $\approx$2 g of Ne, $\approx$2 g of Ar, $\approx$1 g of Kr, and $\approx$1 g of Xe) (*Haskin and Warren,* 1991). The upper 2 m of the lunar regolith thus contains $\approx 7.6 \times 10^9$ tonnes of N, $\approx 1.5 \times 10^{10}$ tonnes of C, $\approx 3.6 \times 10^{11}$ tonnes of S, and $\approx 2 \times 10^{11}$ tonnes of P, along with the $\approx 7.6 \times 10^9$ tonnes of H (Fig. 1).

In terms of life support, these amounts are enormous. Each cubic meter of typical lunar soil contains the chemical equivalent of lunch for two—two large cheese sandwiches, two 12-oz sodas (sweetened with sugar), and two plums, with substantial N and C left over. The quantity of N in a 75-kg human corresponds to the amount present in only 36 m^3 of soil, or an area of 6 m × 6 m mined to 1 m depth. The $\approx$200 g C per square meter of lunar surface compares favorably to the estimate of 540 g of C per square meter of the Earth's surface in living organisms (*Borchert,* 1951). Thus, the total mass of lunar C corresponds to the average amount of terrestrial C in living organisms in an area of Earth as large as 1.4 times that of the United States. Collection of even a small fraction of the Moon's budget of H, C, N, P, S, and other elements essential to life into a suitable environment on the Moon would support a substantial biosphere.

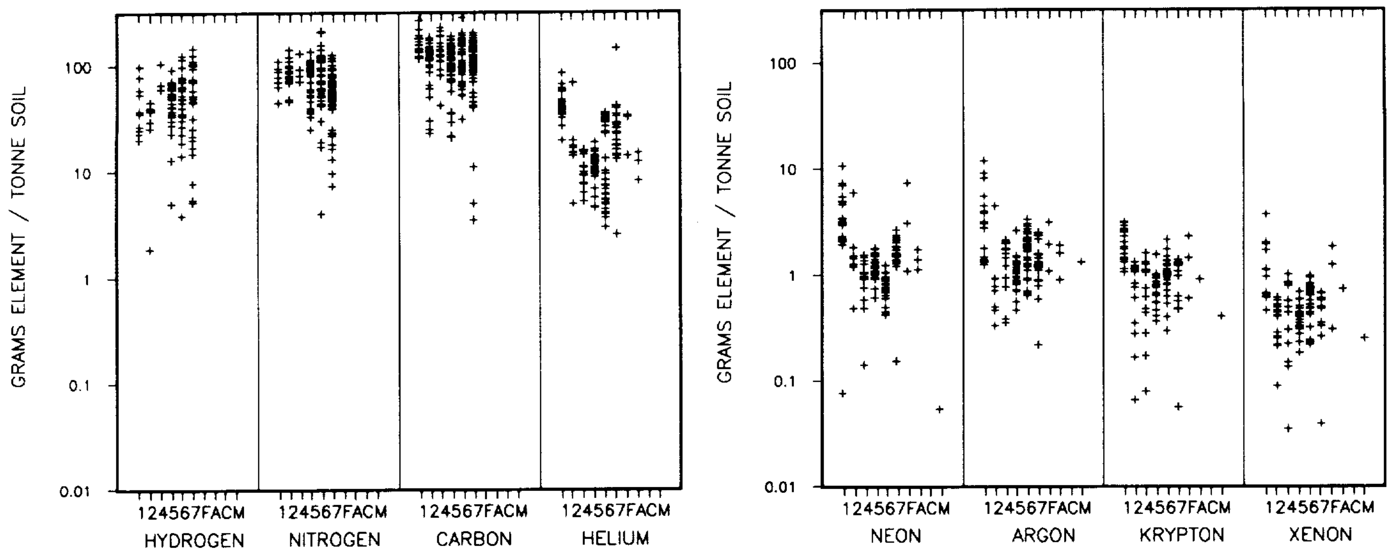


Fig. 1. Concentrations of H, C, N, and noble gases are shown for individual lunar soils from various lunar sites. Included with the data for soils are data for several regolith breccias, which have many characteristics in common with soils. Units are grams of element per tonne of soil (or μg element per g soil). The Apollo landing sites are denoted by the numbers 1, 2, 4, 5, 6, and 7 for the Apollos 11 through 17 missions. The Luna sites are F, A, and C (for Fecunditatis, Apollonius, and Crisium). The Antarctic meteorites, which represent one or more unknown highland sites, are denoted M. The database and format for the figure are based on *Haskin and Warren* (1991).

The current economically appealing use foreseen for these resources is for propellant. In particular, lunar H as a fuel for spacecraft would enhance the value of lunar O as an oxidizer, because then neither H nor O would have to be hauled to low Earth orbit (LEO) from Earth. An annual rate of use of $\approx$300 tonnes/year for lunar O has been estimated for movement of satellites from LEO to geostationary orbit (GEO) toward the end of this century. The corresponding (unfavorably high) stoichiometric amount of H is only 40 tonnes/year. Even at a rate of use a hundred times that, the supply of H would last nearly two million years.

For further perspective, the external tank on the space shuttle contains about 100 tons of liquid H_2 at liftoff. The radius of the crater (without rays) Copernicus is of the order of 100 km. The amount of H beneath an area of regolith equivalent to the area of Copernicus is some 1.6 million tonnes, or enough for 17,000 shuttle tankloads. The greatest amount of H that could be used for propellant during the next several decades would not leave strip mine scars visible to the naked eye on Earth.

There simply is no shortage of H, C, N, or O at the lunar surface. These elements occur in a manner unlike that to which we are accustomed on Earth. All except O can be readily extracted into the gas phase in high yield by heating of lunar soil, and some O is extracted along with the H. On heating of soils, most H is evolved as H_2O or H_2 by the time a temperature of 700°-800°C is reached (e.g., *Gibson and Moore,* 1972), although some H is not removed until the melting temperature of 1050°-1100°C is approached or reached (e.g., *DesMarais et al.,* 1972). Substantial fractions of C are also removed by heating to 700°-800°C, but temperatures as high as 950°-1000°C are required to remove substantial fractions of the N, and temperatures $\geq$1200°C appear to be required to remove C and N quantitatively (e.g., *Simoneit et al.,* 1973; *Chang et al.,* 1972; *DesMarais et al.,* 1972). Thus, the problem of accessibility of H, C, and N reduces to one of the economics of heating substantial quantities of lunar soil, capturing the evolved gases, and separating the different gaseous components from each other.

A ROUGH ESTIMATE OF PARAMETERS FOR EXTRACTION OF HYDROGEN

Hydrogen may be extracted from lunar material by innovative processes not based on simple heating of lunar material (e.g., biological extraction; *White and Hirsch,* 1984). Hydrogen and the other solar-wind-implanted, relatively volatile elements may conceivably become available in great quantities as by-products of some other venture, e.g., the mining of ^{3}He. It has been suggested that lunar ^{3}He could be mined in large quantities to provide fuel for fusion reactors that would supply the bulk of Earth's power for many decades (*Wittenberg et al.,* 1987). That isotope, which could possibly replace radioactive ^{3}He in the most commonly considered type of controlled fusion, is more dilute relative to ^{4}He on the Earth than in the lunar soil. A substantial portion of the lunar surface might be mined to obtain ^{3}He, and H, C, N, and other noble gases would be extracted along with it. If this were to take place, we would be faced with capturing and conserving an embarrassingly high amount of H, C, and N. From here on, we ignore that possibility and consider the production of H for use on the Moon or in LEO, mainly as rocket fuel for transport of spacecraft between LEO and GEO. Given below are estimated parameters for producing 40 tonnes of H per year and the assumptions underlying those parameters.

At $\approx$100 g H per m^3 (>50 g H per tonne) of lunar soil (density about 1.75 to 2 g/cm^3), roughly 8×10^5 tonnes of soil must be processed per year. Assume that solar heating will be used, and

that processing is done only 120 (24-hour) days per year. Then, 3800 m^3 (6700 tonnes) of soil must be processed per day.

Assume that the bulk of the H will be released by 700°C. We estimate the heat capacity of lunar soil to be ≈0.3 cal/°C/g [the measured values of *Hemingway et al.* (1973) go only as high as 300 K]. The heat required to warm one day's worth of soil to 700°C is thus $\approx 1.4 \times 10^{12}$ calories. This amounts to some 63 MW of power, a very substantial amount. However, most of the heat can be recovered following the extraction step and used to preheat the incoming feedstock. Thus, only a few megawatts of power will actually be required if the power can be delivered efficiently.

This heat can be obtained from the sun. During the 120 days of greatest light, the solar energy flux averages roughly 10^{-3} MW/m^2. If we can transfer solar energy to the extraction chamber and use it with 80% efficiency, then we need about 12 MW of solar flux. This corresponds to the energy falling on an area of ≈1000 m^2, or a 32-m square. It may be a challenge to collect and focus this energy, but the energy is certainly there. It may be more practical to convert the energy from direct heat to some other form (e.g., microwaves; *Meek et al.,* 1984; *Tucker et al.,* 1984) to concentrate it into the relatively small volume of the processing chamber, especially since the soil is an excellent insulator. In that case, the efficiency would be lower, and a larger area of collection would be necessary.

The conductivity of lunar soil has been measured *in vacuo* (*Hemingway et al.,* 1973), but not under pressure of gas, and moving gas is an effective heat transfer agent. In fact, the gas pressure will be substantial and will (or through appropriate engineering design could be made to) affect the rate of heat transfer. Some 70 mols of gas per cubic meter of soil will be produced. Soil porosity is normally ≈40%, since the bulk density is ≈1.75 g/cm^3 but the particle density approaches 3 g/cm^3. At 700°C, the ≈70 mols of gas produced per cubic meter of soil would produce a pressure within the pore space of ≈14 atm. This might be sufficient pressure to drive a turbine to stir the soil to increase the rate of heat transfer, or to pump the gas, etc. The reversible isothermal expansion of 70 mols of gas per cubic meter of lunar soil from 14 atm to 1 atm corresponds to a power rate of 65 kW for the 3800 m^3/day of soil processed. Taking mechanical advantage of the pressure affects reactor design.

If the gas is removed from the system at low pressure, the anticipated low permeability of the soil on the incoming side might be expected to prevent the gas from leaking out of the entry port in a continuous feed system. (The mean particle size of lunar soils is quite small, e.g., ≈40-80 mm for mature soils from Apollo 17; *McKay et al.,* 1974.) If the gas were allowed to build up to its full pressure (≈14 atm), however, the back pressure would equal that of a column of soil some 470 m tall.

The required flux rate of soil through the chamber also depends on the efficiency of heat transfer. If we assume that in the extraction chamber the soil can be heated to the necessary 700°-800°C in one minute, and we assume a cross section for the chamber of 10 cm height by 2 m width, the length of the chamber has to be 13 m to accommodate the throughput of 3800 m^3 of soil per day. The velocity of the soil would have to be 0.78 km/hr (22 cm/sec), and the residence time of the soil in the chamber would be about 1 min. These calculations are meant to illustrate that sizes and rates are within the range of feasibility, and should not be taken as an attempt to design a reactor.

At the time of mining or some time prior to gas extraction, the soil would need to be sieved to remove particles of large enough diameter to interfere with any moving parts of the reactor, for example, the minor portion consisting of particles of diameter >5 mm. (Since material of diameter >5 mm is relatively rare in the regolith, the gravel thus collected could be a valuable by-product of the process.) The solar wind is implanted mainly at the surfaces of soil grains, so concentrations of solar-wind-implanted elements are somewhat surface correlated. Thus, sieving the soil to obtain a fine size fraction would thus produce a richer feedstock. *Carter* (1984) has discussed in detail the possible advantages of sieving the soil and subjecting only the finest fraction to the extraction process. He demonstrates that two-thirds of the H is present in the <20-mm portion of most soils. Whether it is better to highgrade the soil or simply to remove only those particles large enough to damage the reactor becomes one of economics; sieving to such a fine size would add significantly to the difficulty of handling the soil, but would reduce the amount of soil that had to be heated.

The volume of soil to be processed per day, 3800 m^3, must be handled twice, on input and after extraction. If the soil is mined to a depth of 1 m, the area of excavation per day would be 62 m × 62 m, roughly comparable to that of a football field, a modest amount by terrestrial mining standards and only about 2% of that required to provide the ^3He needed to support a 500-MW fusion power plant (e.g., *Li and Wittenberg,* 1991). In a year's time, the total amount of soil moved (120 days' worth, moved twice) would be 9×10^5 m^3. This corresponds to excavation and replacement of the soil to 1-m depth within a radius of 380 m of the extraction plant over a year's time. This would be a substantial, but not a formidable, challenge to early lunar technology.

The gaseous products of the heating would include H_2O, H_2S, CO, CO_2, NH_3, HCN, and noble gases (e.g., *Simoneit et al.,* 1973). The easiest means of separating the components from each other may begin with combustion to produce H_2O, CO_2, N_2, SO_2, and noble gases, then use differential freezing or adsorption to separate the combustion products from each other. For this, perhaps advantage can be taken of the low temperature (-170°C) of shaded regions on the Moon and of the adsorptive capacities of lunar soils. *Fuller et al.* (1971) and *Cadenhead et al.* (1972) give parameters for lunar soils for adsorption and desorption of gases.

CONCLUSIONS

The Moon should not be overlooked as a source for H, C, or N for use in space, for either life support or rocket fuel. Available quantities of all three elements are substantial. These elements are released as gaseous elements and compounds when lunar soils are heated to high temperatures. This method of extraction is quite unlike those used to obtain these materials on Earth, but the sun can serve as the principal source of energy for the processes. The likely method of extraction of water from martian soil (the regolith tested by the Viking mission contains 0.1-1 wt% H_2O) is heating, but only to 350°-500°C (*Biemann et al.,* 1976). Pyrolysis to 500°-600°C is also the probable method of extracting these materials from near-Earth asteroids, based on the assumption that some of them will prove to be similar in character to Carbonaceous meteorites (e.g., *Simoneit et al.,* 1973). The trade-off is one of ease of access (and, for the present, certain knowledge of the nature of the lunar regolith) and higher extraction temperatures vs. far more distant, poorly characterized sources and somewhat lower temperatures.

Acknowledgments. Thanks to R. Colson, B. Jolliff, and C. Keedy for helpful suggestions regarding the content and presentation of this material. This work was supported in part by the National Aeronautics and Space Administration under grant NAG-956.

REFERENCES

Arnold J. R. (1979) Ice in the lunar polar regions. *J. Geophys. Res., 84,* 5659-5668.

Biemann K., Oro J., Toulmin P., Orgel L., Nier A., Anderson D. M., Simmonds P. G., Flory D., Diaz A. V., Rushneck D. R., and Biller J. A. (1976) Search for organic and volatile inorganic compounds in two surface samples from the Chryse Planitia region of Mars. *Science, 194,* 72-76.

Borchert H. (1951) Zür geochemie der kohlenstoffs. *Geochim. Cosmochim. Acta, 2,* 62-75.

Bustin R., Kotra R. K., Gibson E. K. Jr., Nace G. A., and McKay D. S. (1984) Hydrogen abundances in lunar soils (abstract). In *Lunar and Planetary Science XV,* pp. 112-113. Lunar and Planetary Institute, Houston.

Cadenhead D. A., Wagner N. J., Jones B. R., and Stetter J. R. (1972) Some surface characteristics and gas interactions of Apollo 14 fines and rock fragments. *Proc. Lunar Sci. Conf. 3rd,* pp. 2234-2257.

Carter J. L. (1985) Lunar regolith fines: A source of H. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 571-581. Lunar and Planetary Institute, Houston.

Chang S., Smith J., Sakai H., Petrowski C., Kvenvolden K. A., and Kaplan I. R. (1972) Carbon, nitrogen, and sulfur released during pyrolysis of bulk Apollo 15 fines (abstract). In *The Apollo 15 Samples* (J. W. Chamberlain and C. Watkins, eds.), pp. 291-293. The Lunar Science Institute, Houston.

DesMarais D. J., Hayes J. M., and Meinschein W. G. (1972) Pyrolysis studies of carbon in lunar fines and rocks (abstract). In *Apollo 15 Lunar Samples* (J. W. Chamberlain and C. Watkins, eds.), pp. 294-298. The Lunar Science Institute, Houston.

DesMarais D. J., Hayes J. M., and Meinschein W. G. (1974) The distribution in lunar soil of hydrogen released by pyrolysis. *Proc. Lunar Sci. Conf. 5th,* pp. 1811-1822.

Fuller E. L. Jr., Holmes H. F., Gammage R. B., and Becker K. (1971) Interaction of gases with lunar materials: Preliminary results. *Proc. Lunar Sci. Conf. 2nd,* pp. 2009-2019.

Gibson E. K. and Moore C. B. (1972) Inorganic gas release and thermal analysis study of Apollo 14 and 15 soils. *Proc. Lunar Sci. Conf. 3rd,* pp. 2029-2040.

Gibson E. K., Bustin R., and McKay D. S. (1988) Lunar H: A resource for future use at lunar bases and space activities (abstract). In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century,* p. 93. Lunar and Planetary Institute, Houston.

Haskin L. A. and Warren P. W. (1991) Chemistry. In *Lunar Sourcebook* (G. H. Heiken, D. T. Vaniman, and B. M. French, eds.), pp. 357-474. Cambridge Univ., New York.

Hemingway B. S., Robie R. A., and Wilson W. H. (1973) Specific heats of lunar soils, basalt, and breccias from the Apollo 14, 15, and 16 landing sites, between 90 and 350 K. *Proc. Lunar Sci. Conf. 4th,* pp. 2481-2487.

Lanzerotti L. J. and Brown W. L. (1981) Ice in the polar regions of the moon. *J. Geophys. Res., 86,* 3949-3950.

Li Y. T. and Wittenberg L. J. (1992) Lunar surface mining for automated acquisition of helium 3: Methods, processes, and equipment. In *The Second Conference on Lunar Bases and Space Activities of the 21st Century,* this volume.

McKay D. S. and Williams R. J. (1979) A geologic assessment of potential lunar ores. In *Space Resources and Space Settlements* (J. Billingham and W. Gilbreath, eds.), pp. 243-255. NASA SP-428, NASA Johnson Space Center, Houston.

McKay D. S., Fruland R. M., and Heiken G. H. (1974) Grain size and the evolution of lunar soils. *Proc. Lunar Sci. Conf. 5th,* pp. 887-906.

Meek T. T., Vaniman D. T., Cocks F. H., and Wright R. A. (1985) Microwave processing of lunar materials: Potential applications. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 479-486. Lunar and Planetary Institute, Houston.

Simoneit B. R., Christiansen P. C., and Burlingame A. L. (1973) Volatile element chemistry of selected lunar, meteoritic, and terrestrial samples. *Proc. Lunar Sci. Conf. 4th,* pp. 1635-1650.

Tucker D. S., Vaniman D. T., Anderson J. L., Clinard, F. W. Jr., Feber R. C. Jr., Frost H. M., Meek T. T., and Wallace T. C. (1985) Hydrogen recovery from extraterrestrial materials using microwave energy. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 583-590. Lunar and Planetary Institute, Houston.

White D. C. and Hirsch P. (1985) Microbial extraction of hydrogen from lunar dust. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 591-602. Lunar and Planetary Institute, Houston.

Wittenberg L. J., Sarantius J. F., and Kulcinski G. L. (1987) Lunar source of ^{3}He for commercial fusion. *Fusion Technol., 10,* 167-178.

FIRST STEPS TO LUNAR MANUFACTURING: RESULTS OF THE 1988 SPACE STUDIES INSTITUTE LUNAR SYSTEMS WORKSHOP

N93-13977

Gregg E. Maryniak

Executive Vice President
Space Studies Institute
P.O. Box 82
Princeton NJ 08542

Prior studies by NASA and the Space Studies Institute have looked at the infrastructure required for the construction of solar power satellites (SPS) and other valuable large space systems from lunar materials. This paper discusses the results of a Lunar Systems Workshop conducted in January 1988. The workshop identified components of the infrastructure that could be implemented in the near future to create a revenue stream. These revenues could then be used to "bootstrap" the additional elements required to begin the commercial use of nonterrestrial materials.

The concept of using nonterrestrial and, particularly, lunar materials for the construction of solar power satellites, free-flying space habitats, and other economically, scientifically, and politically interesting structures in space has been gathering momentum for almost 15 years. Favorable recommendations in the National Commission on Space Report, chaired by Dr. Thomas Paine, and the special NASA study prepared by Astronaut Sally Ride have accelerated national and international interest in this area.

Although the overall concepts first published by Dr. Gerard K. O'Neill in 1974 in his article "The Colonization of Space" (*O'Neill,* 1974) still represent current thought, the systems concepts involved in the use of lunar resources have evolved considerably. As observed from the vantage point of the Space Studies Institute, a nonprofit organization founded in 1977 to conduct critical path research on the use of nonterrestrial resources, this evolution has taken place in four phases. The initial period of systems studies on nonterrestrial materials systems took place between 1974 and 1977. In addition to three Princeton University conferences on the subject (AIAA), there were three major NASA-supported summer studies that took place during 1975, 1976, and 1977 (*Johnson,* 1979; *O'Neill and O'Leary,* 1977; *Billingham et al.,* 1979). Studies in this era generally assumed implantation of full-scale systems on the Moon and in space with costs commensurate with that of the entire Apollo program (on the order of $60 billion).

The second era of systems thinking took place during the years 1977 and 1978. Building on the successsful demonstrations of Mass-Driver I, a prototype electromagnetic launcher constructed at M.I.T. by Professor Henry Kolm, O'Neill, and a group of graduate students, O'Neill continued to look for ways to reduce the investment required to produce economic returns from a nonterrestrial materials scenario. This work culminated in an article entitled "The Low (Profile) Road to Space Manufacturing" (*O'Neill,* 1978). This article suggested that by taking a step-wise approach to the build-up of the space infrastructure, significant reductions in system cost could be obtained. This incremental building approach was coupled with the concept of using the shuttle external tank as reaction mass for a Mass-Driver reaction engine. The combination of this low-cost, high-tonnage, orbital transfer vehicle and an incremental build-up reduced the investment required to obtain "ignition point" from $60 billion to approximately $24 billion. Ignition point was defined as the point where revenues earned equal investment.

During this same time period, the Space Studies Institute was founded to guarantee the continuation of nonterrestrial materials research. The third systems evolution occurred as the result of a series of workshops sponsored by the Institute in 1979 and 1980. These workshops examined various scenarios in an attempt to minimize start-up costs and to maximize growth of the system's ability to throughput lunar materials. The results of these workshops were detailed in an article entitled "New Routes to Manufacturing in Space" (*O'Neill et al.,* 1980). Figure 1 shows the three prime scenarios considered by the workshop groups. The favored scenario involves placing 100,000 kg of equipment on the lunar surface and approximately the same amount of equipment in free space. This is distributed over three general components. The first of these is a small lunar base that operates a Mass-Driver launcher to transport lunar materials to a collection point in space and that also has the capability of making partial copies of additional Mass-Drivers. The second component is a mass catcher to collect the launch materials. The third component is a space manufacturing facility, or "job shop," that processes the lunar materials and makes parts for additional Mass-Drivers, mass catchers, and job shops. Although the workshop concluded that it does not make sense to try to replicate the labor-intensive computers and precision components of machine tools, it reported that such a system could manufacture 95% of its own mass in a 90-day timeframe. Assuming the existence of orbital transfer vehicles and lunar landers, the cost of implanting the first such seed for the exponential growth of space industry would be about $6 billion. This is of the same order as the Alaska Pipeline or a pair of Magnus-class North Sea oil rigs.

Between the 1980 workshops and the 1988 Lunar Systems Study, a wide range of research on the use of nonterrestrial materials has been carried out by the Space Studies Institute.

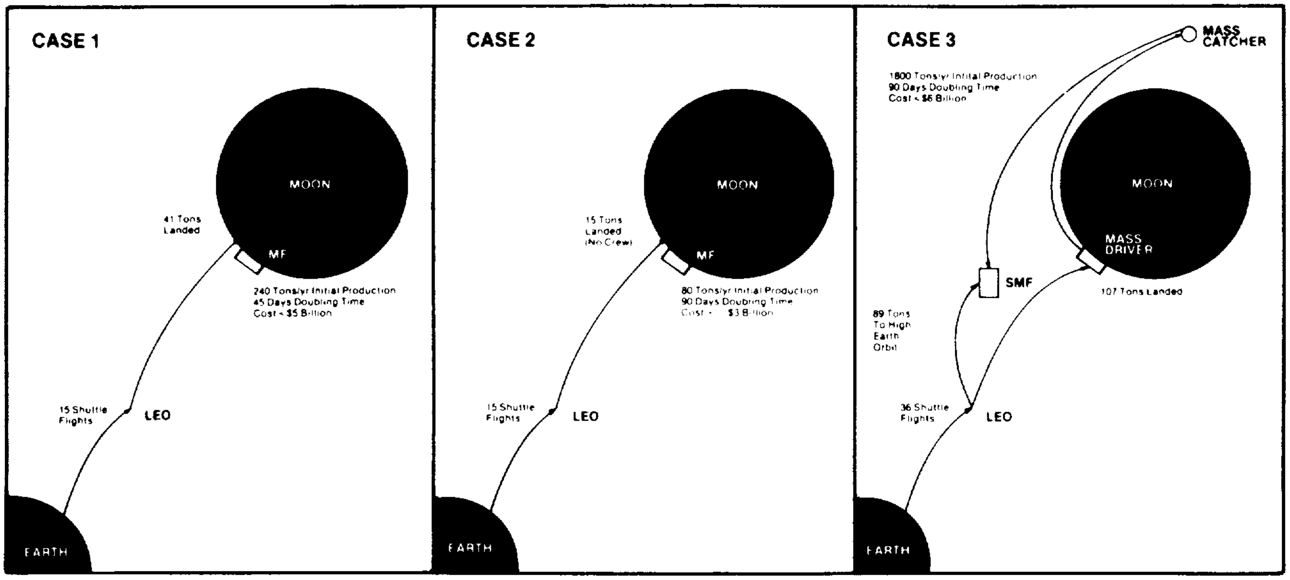


Fig. 1. "New Routes" Workshop Scenarios (1980). **Case 1.** Partially self-replicating system, with industrial operations only on the lunar surface. **Case 2.** Totally automated lunar-based system. **Case 3.** Partially self-replicating system on Moon and in orbit. Equipment on Moon used for replication of mass-drivers; equipment in space used for replication of wide range of components.

The results of these research projects can be found in the Proceedings of the SSI-sponsored conferences on Space Manufacturing held in 1974 and biennially since 1975. Table 1 shows the dates of the conferences and cosponsoring publishing organizations. Highlights of this research program have included a series of prototype Mass-Drivers constructed at Princeton University with accelerations ranging from 500 to 1800 *g*. A Mass-Driver with a 33-*g* acceleration (such as that exhibited in the first test of Mass-Driver I) would require an acceleration section of approximately 5 miles in length. With Mass-Driver III performance (1800 *g*), the length of the accelerator would be about 500 ft.

A hydrofluoric acid leach chemical processing technique has been demonstrated by SSI at a bench-scale level. Under Institute contract, Dr. Robert Waldron of Rockwell International conducted a series of experiments to determine upper limits to reaction times and impurity levels of the two most critical reagent elements, fluorine and hydrogen, in the output oxides produced by such a system. He produced a sizing analysis based on equipment and reagent inventory mass, and on power and cooling requirements necessary to the system. Key findings of this research include the determination that reagent replacement requirements appear to be less than 0.1% of the throughput mass of the system, and that by using the initial output of the system to manufacture additional plant equipment, a small starter plant made up of about 90% reagent material (by mass) could grow into a facility that would annually process about 500 times the original Earth import mass (*Waldron,* 1985).

TABLE 1. SSI/Princeton University conferences.

1974	AIAA	Vol. 1
1975	AIAA	Vol. 1
1977	AIAA	Vol. 2
1979	AIAA	Vol. 3
1981	AIAA	Vol. 4
1983	Published by AAS	
1985	AIAA	Vol. 5
1987	AIAA	Vol. 6

Conference proceedings for these years are available from the AIAA.

We have examined the use of the shuttle's expendable external tanks as a source of aluminum, hydrogen, and oxygen, in addition to applications as a structural element or pressure vessel.

We are developing the initial fabrication of glass and glass composite materials so that they can eventually be made entirely from lunar sources. In addition to requiring considerably less processing than metals chemically separated from lunar soil, these composites will have excellent thermal properties and may be used for structural beams as well as pressure vessels. A companion paper by principal composites investigator Brandt Goldsworthy was presented at this conference.

The Space Studies Institute has sponsored a design of the solar power satellite optimized for construction from lunar materials. The principal barrier to the development of large-scale space solar power systems for delivery of energy to the surface of the Earth is the cost of transporting construction materials from the surface of the Earth to construction sites in orbit. Although a Department of Energy and NASA study on implementing such an Earth-launched system was favorable (*U.S. Dept. of Energy,* 1980), a National Academy of Sciences overview study disagreed, largely on the basis of transportation costs (*National Research Council,* 1981). Studies performed by M.I.T. (*Miller and Smith,* 1979) and the Convair Division of General Dynamics (*Bock,* 1979) looked at substituting lunar material for terrestrial material in solar power satellite construction. However, both these studies were limited to using the Earth reference baseline for their design. Even so, the General Dynamics study suggested that 90% of an SPS could be lunar in mass, and the M.I.T. study indicated 96% of the mass could be lunar. A design study instituted by SSI was optimized not on low-launch weight but, instead, upon maximum use of lunar resources. Under contract to SSI, Space Research Associates of Seattle, Washington, designed a silicon planar solar power

satellite that contained over 99% lunar materials. Figure 2 shows a mass comparison between the Earth baseline (Boeing) design, the General Dynamics lunar materials substitution design, and the Space Research Associates 1985 lunar design. The lunar design resulted in significant cost savings (97% less than the Earth baseline design) with a transport cost ratio assumed to be 50:1 for lunar materials. Furthermore, the lunar design was only 8% heavier than the Earth baseline (*Space Research Associates,* 1985).

The Institute also commissioned a study on the use of beamed power for space transportation (*Sercel,* 1986).

1988 WORKSHOP

In January 1988, a group of researchers convened at the GE Astro Space facility just outside Princeton, New Jersey, to reexamine the growth of a lunar systems infrastructure. The group agreed that its target would be to create one or more scenarios or business plans for the productive use of lunar materials. Our philosophy was that independent, profit-making space businesses could provide a robust, nonreversible course into space.

Under the direction of Dr. O'Neill, the group established a series of assumptions. All necessary political and regulatory approvals were assumed as given. Each business, or business stage, would have to reach revenue in five years from its first substantial investment, with profits within an additional two years. Although full cooperation of governments was assumed, no subsidies other than those already built into standard launch fees would be assumed. No launch vehicle not already developed could be used for planning purposes; however, any launch vehicle, including the Soviet Energia, could be specified. The existence of a fully reusable vehicle (or cooperating pair of vehicles) capable of transferring cargo and, if necessary, people between low Earth orbit (LEO) and the lunar surface was assumed. Viable businesses must produce at least 20% per year compounded return on investment.

Dr. Peter E. Glaser advised the group to think of space as being no different from the surface of the Earth in terms of economics. In effect, all terrestrial economic ground rules will still hold true on the high frontier. Further, he suggested that each new step that we take should not only provide economic return but should also provide a foundation for the next development step. That is, we should use a "terracing" approach to space development.

The workshop team was unanimous in the long-range goals of the space infrastructure system. Ultimately, such a system should

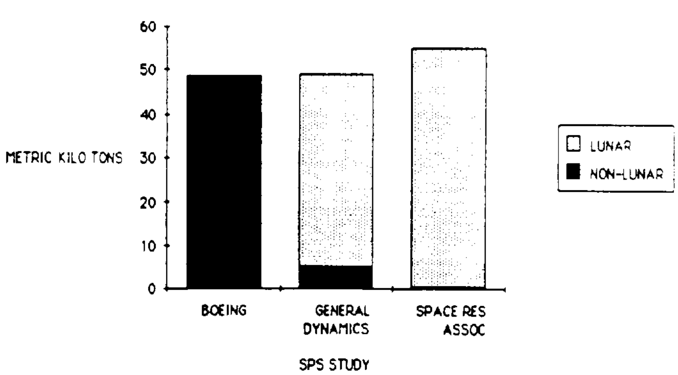


Fig. 2. 5 GW to Earth.

be capable of processing sufficient lunar materials to enable the construction in free space of solar power satellites and eventually space habitats. However, it was also clearly understood that while the creation of such a system is technically possible, from a financial standpoint, the risks are presently too great and the payback period too long to make such a system fit our study criteria if accomplished in one effort.

Although the supply of lunar-derived oxygen has been widely discussed (*Andrews and Snow,* 1981) and appears to be a particularly attractive option for supplying exploration missions beyond cislunar space (*Woodcock,* 1988), it will require considerable infrastructure building to initiate and could not, in and of itself as a stand-alone enterprise, fall within the limits set by our study assumptions. We therefore decided to look at the subcomponents of our ultimately desired, nonterrestrial materials manufacturing scenario to identify the locations of critical nodes. We then created subteams to explore business plans for operations that could profitably develop at each of the nodal locations prior to the operation of the eventual total system.

Teams were created in each of the following areas: LEO node, space transportation, space power development, lunar surface operations, and space manufacturing.

LOW EARTH ORBIT NODE

One of the underlying assumptions of the study was the existence of an orbital transfer vehicle and a lunar landing system to connect the surface of the Moon with LEO. These space transportation system components will require an LEO node for fueling payload integration and servicing. The LEO node group (F. Bailiff, D. Andrews, and A. Gimarc) looked at markets that could be serviced from an LEO facility, which could also service the lunar transportation system and return early revenues.

Several assumptions were made by the group. First, external tanks of the space transportation system are available for salvage. (This assumption was made approximately two months before the White House National Space Policy announcement that external tanks would be made available to corporations in orbit.) Second, residual propellants are assumed to be available for scavenging at cost. Also Orbiting Maneuvering Vehicle (OMV) sorties as well as Expendable Launch Vehicle (ELV) and shuttle sorties are assumed available at cost. Payload insurance is also assumed to be available at a price of 30%. The LEO group also defined two categories of markets. The first was a group of early markets. These included a storage facility for experiment racks and equipment for the U.S. and other space stations, a waste management facility, again assumed to be colocated with a space station, a volatiles storage facility, primarily for the storage of propellants, and a man-tended facility for experiments that could provide communications, power, and waste heat radiation.

Later markets that could be serviced by this node include a cryogenic storage and a refueling facility for OTV/OMV, a construction facility for the outfitting of additional external tank-based equipment, and a payload rescue capability to recover space equipment that had been placed in improper orbits or that required propellants or other servicing to extend their lifetime. Other possible markets are the rental of volume to commercial users, payload mating and launch to higher orbits, and training for commercial customers.

Growth of this type of commercial enterprise is expected to occur in three phases defined as follows. Phase I involves the buildup of a man-tended external tank plus a services module to

provide internal storage, volatiles storage, waste management facility, and external support of commercial/scientific experiments. Phase II involves the buildup of a manned construction facility/commercial floor space and support, payload integration, OMV servicing and support, ELV payload support, shelter, and training of commercial crews. During Phase III a large, tethered cryogenics storage facility will be constructed and OTV support established.

Phase I would be a man-tended, single external tank and services module that would consist of a modified external tank with a services module and solar array located in a 28.5° orbit along the velocity vector of the space station. External tank modifications include internal hatches, tankage for propellants in the intertank section, external mounting in brackets, modification of the external tank tip for orbital maneuvering vehicle docking, and internal hardware in the hydrogen tank for storage of equipment racks. Additional support equipment includes the service module, teleoperators, a docking system, an electolysis reboost system, waste management, micrometeorite bumper, thermal shielding, communications, power, and miscellaneous support equipment. Start-up costs and potential market costs for Phase I are listed in Tables 2 and 3.

Phase II is a manned construction facility. The purpose of this unit would be the refitting of surplus external tanks for other commercial users. This phase would also include the introduction of the propellant scavenging operation and the development or purchase of a free-flying scavenger that could double as a manned OMV/OTV. Phase II would also involve the attachment of a space station logistics model to the second external tank, preparation of the hydrogen tank interior for shirt-sleeve environment, outfitting of the logistics module for manned habitation, and design and preparation for the launch of a future construction platform.

A second STS sortie will be purchased for delivery of the external tank, logistics module, and scavenger to the Phase I platform. A second 25-kW solar array would be attached. The interior of the second external tank would be made habitable for an initial crew of 8, which can be expanded to 24. A medium-lift ELV sortie (a Titan 4 or Proton class vehicle) would be purchased to deliver the construction platform, tools, and support equipment to the facility. If an external tank Aft Cargo Carrier (ACC) were available at reasonable cost in this timeframe, it could be purchased in place of the logistics module. (Phase II start-up costs were also computed and can be found in Tables 4 and 5.)

Phase III of the buildup of this node is a cryogenic storage depot. This requires the addition of a third external tank and module combination to the construct. This addition enables the node to service OTVs and lunar operations. The support module is configured for the reliquification of delivered oxygen and hydrogen and is used initially for the refueling of reusable OTVs. It is tethered below the initial Phase I and Phase II components. Estimated Phase III start-up costs and revenues are computed in Table 6.

The assumption that the tankage will be necessary at the rate of six OTV sorties is consistent with space station planning. Every traffic model that assumes a reasonable growth of activities in space requires some sort of cryogenic storage and servicing facility.

In summary, the commercial operation of an LEO services complex can, in its early stages, provide valuable warehousing, housekeeping, and other services to the space station, and in later phases it can service Earth and orbit lunar OTVs and show

TABLE 2. Start-up costs for Phase I.

Facilities	Cost ($ million)
Modified External Tank	1.00
Orbital Mods/Bumper	5.00
Logistics Module	20.00
Docking Adapter	0.25
Thermal/Comm/GN&C	1.00
Power 0.25 kWe	2.50
Electrolysis Reboost	10.00
Teleoperators (2)	10.00
Shuttle Launch	120.00
Insurance	15.00
Total	185.00

TABLE 3. Potential market costs for Phase I.

Market	Cost ($ million)
Garbage/Waste disposal- $1000/lb	15.00
Equipment storage- $1 m/rack/year	25.00
Volatiles storage- $1000/lb/yr at 10,000 lb/OMV sortie	10.00
Payload attach services- STS pallets flat - $2m/variable - $10m/(×2)	24.00
ELV grab - $3m/OMV sortie & Flat & Variable (Note: OMV sortie is additional charge) (×2)	24.00
Power Supplied- $0.5m/kWe/yr	4.00
Big LDEF facility- $1 m/experiment/yr	10.00
Total	112.00

TABLE 4. Start-up costs for Phase II.

Facilities	Cost ($ million)
Modified External Tank	5.00
Scavenger - Manned*	75.00
MLI/Bumpers/Attachments/Docking Adapters	5.00
Logistics/Service Module	25.00
Power (25 kWe)	2.50
Totals (approx.)	115.00
ELV Launch	50.00
Shuttle Launch	120.00
Insurance (30%)	35.00
Total	320.00

* Capacities: 30,000 lb LOX, 2000 lb LH_2, 1540 lb N_2O_4, and 960 lb MMH.

TABLE 5. Low Earth orbit node operations.

	Costs ($ million)	Sales ($ million)
Outfitting 4 ET/Yr	590.00	1180.00
ET & Module & Misc.		
Assembly - EVA $20K/hr	5.00	75.00
Assembly - IVA $3K/hr	5.00	6.00
10 Scavenger Flights	20.00	
Payload Rescue	10.00	60.00
6 OMV Refuelings		18.00
Totals	630.00	1339.00

TABLE 6. Start-up costs for Phase III.

Facilities	Cost ($ million)
Modified External Tank	5.00
Service Module Plus Equipment	55.00
Tanker DDT&E & 2 Copies	50.00
Totals (approx.)	110.00
Shuttle Launch	120.00
Insurance (30%)	33.00
Total	263.00

significant profit potential. An investment of $770 million in equipment facilities, sorties, and insurance could lead to a yearly profit in excess of $1 billion.

Figure 3 shows a drawing by Eagle Engineering artist Pat Rawlings of the LEO node after addition of the tethered Phase III cryogenics handling capability.

SPACE POWER

The space power subgroup (W. C. Brown and L. Snively) investigated means of bootstrapping space power utility systems. Given the relatively low cost of generating electrical power on the surface of the Earth in comparison to the cost of solar electric power in orbit, the group concluded that initial space power utility markets might be serviced by beaming terrestrial power from the surface of the Earth via microwaves or lasers. Markets for these services could include industrial facilities in LEO (*Brown,* 1987a) and might include powering electric propulsion orbital transfer vehicles from LEO to geosynchronous orbit (GEO) (*Brown,* 1987b). The cost required to build the terrestrial infrastructure network needed to support LEO-to-GEO OTVs is high (on the order of $1 billion), although the resulting transportation costs are very competitive with other proposed OTV systems. An alternative concept, recommended for further study by the group, would use terrestrially generated beams via a laser tuned to the optimum frequency for conventional solar cells. This method appears to be optimal from the point of view of low initial costs and acceptable overall transmission efficiences.

A logical progression from these initial systems would be the construction of a small-scale SPS, whose output would be transmitted via laser to users in GEO, LEO, and possibly for Earth-to-Moon OTVs. The size of such a platform (approximately 10 MW) would provide useful amounts of power as well as a test of solar power satellite construction and deployment. This size is consistent with proposals for the creation of a test SPS as an International Space Year project. The key uncertainty for space solar power is the size of the market for transmitted power.

LUNAR SURFACE NODE AND PRECURSOR MISSIONS

Lunar surface activities were explored by the workshop at two different levels including long-term lunar operations, e.g., permanent facilities and equipment, and precursor missions that would enable exploration, technology, development, and sortie mission activity prior to permanent lunar settlement.

Consensus of the group was that the primary product from precursor missions is information. Examples of this type of activity include small lunar-orbiting spacecraft that would provide a resolution of the question of the existence of water trapped as ice in the permanently-shadowed regions near the Moon's poles. Figure 4 shows a simple surface rover that would follow orbital surveys to provide high-resolution chemical, mineral, and perhaps isotopic ground truth in areas mapped by the orbiter as promising for resources. Because a small machine is likely to be upset by obstacles, the vehicles are designed to be self-righting in the manner suggested in the background of the picture. At this stage of development, it is likely that the primary customer for information produced in this manner would remain government entities.

In a sense, information gained from these missions could "bootstrap" other missions, especially if volatiles are located. (While the average man in the street would probably not quit his job because of a rumor of "ice in them thar hills," if water is located in abundance, it will dramatically reduce the costs of lunar transportation beyond initial prospecting missions.) The workshop sought private ventures that could be economically self-

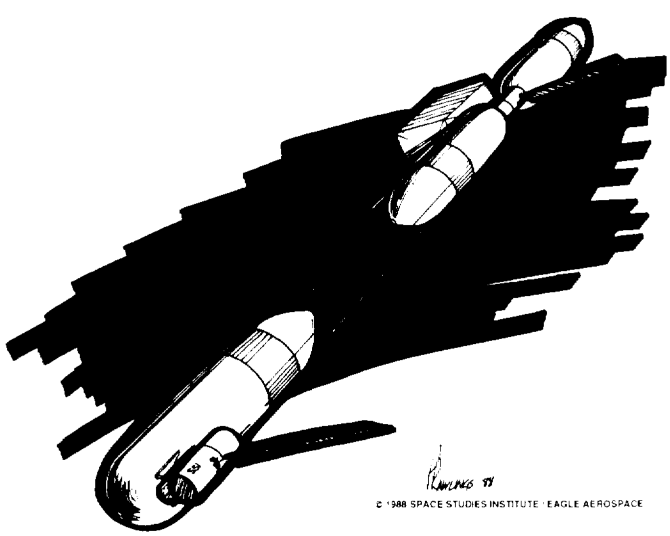


Fig. 3. LEO services node.

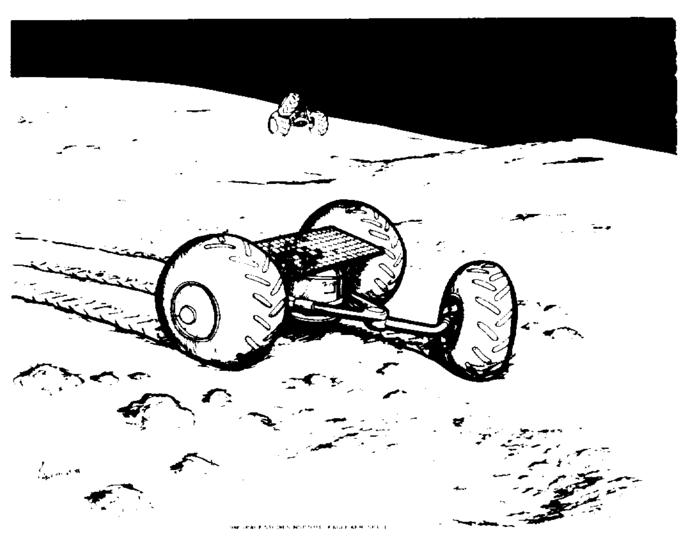


Fig. 4. Early lunar rover for geochemical "ground truth" surveys.

supporting and could provide information, material samples, and technology development without government support.

"A quick payback" subgroup (E. Bock, G. Maryniak, R. Temple, B. Tillotson, and R. Tumlinson) proposed a three-mission scenario of automated landers for an investment of approxiamtely one order of magnitude lower than that required for piloted systems.

The premise of the first mission is that a lunar landing stage is expended by a one-way trip with 10,000 kg of payload to the lunar surface. The payload is made up of six small teleoperated lunar rovers weighing 10,000 kg in aggregate. Two tonnes are devoted to a pilot LOX production plant, 3000 kg are core payload structure in avionics, and 1000 kg is comprised of TV cameras and transmitter, a robot arm and hand, and a demonstration electrostatic or electromagnetic beneficiator. Figure 5 is a drawing of a teleoperator being deployed from the landing stage. The overall cost of the first mission was estimated at $200 million with half that figure devoted to transportation at $11,000/kg predicted on a heavy-lift vehicle of the Energia class.

Most novel of these scenarios is sponsorship for a lunar surface race between some or all of the teleoperated vehicles. Development cost for the vehicles is assumed to be zero to the enterprise, as it is envisioned that these would be constructed by sponsors such as automobile manufacturers in order to obtain promotional consideration (Fig. 6). It was pointed out that the recent solar electric automobile race conducted in Australia was an approximately $20 million venture, just one order of magnitude below the cost of this mission. The rovers can also be used for performing a traverse of a scientifcally interesting region of the Moon, including a possible traverse from Copernicus to Kepler to Aristarchus and Gruithuisen. Tables 7 and 8 detail potential cost and income for such a mission. In addition to the entertainment and advertising aspects of the mission, which would provide consciousness-raising benefits for space development, this first mission would also include a pilot-scale LOX production plant that would process surface materials directly underneath the lander, or possibly those delivered by one of the teleoperators. In addition, one or more of the teleoperators would test magnetic and electrostatic beneficiation pilot models and could cache quantities of beneficiated feedstocks at the landing site throughout the equipment lifetime.

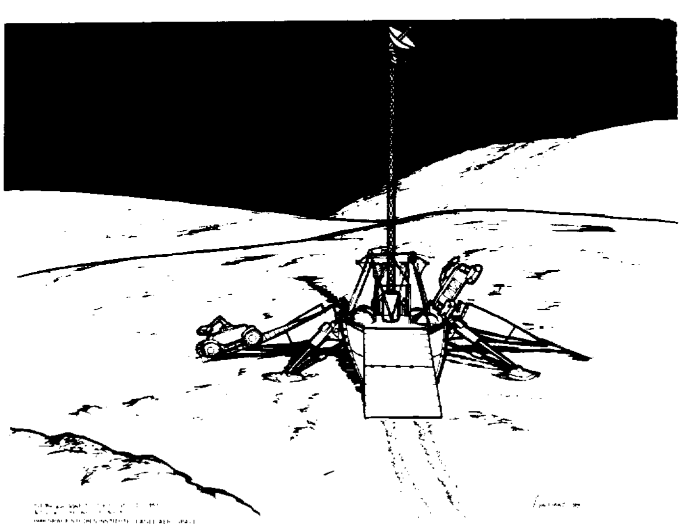


Fig. 5. Lunar lander deploying teleoperated rover.

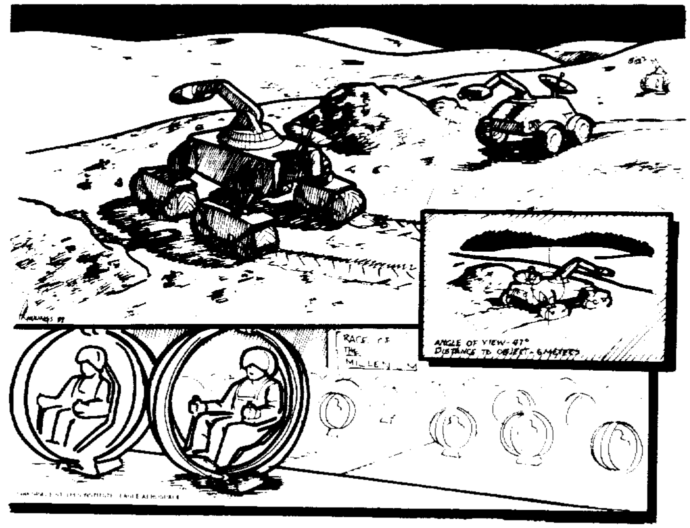


Fig. 6. Lunar teleoperated rover race.

The second mission is also unmanned, but the payload includes a small rocket that can return 1500 kg of selected lunar material to Earth. The automated payload also includes a second-generation LOX production plant to process small amounts of lunar iron and glass into high-value products for sale on Earth, such as lunar iron "coins" and lunar glass jewelry. After landing, adjacent to the first mission payload, iron, glass, and peculiar lunar surface samples collected by the six Mission I rovers are deposited in the Mission II lander. The unprocessed samples and processed coins and jewelry are returned to Earth, recovered, packaged, and sold to the public. The value of this lunar material is dependent on demand, but we have estimated that a price of $300-500 per carat is feasible. This provides rapid mission payback plus significant profits. Table 8 depicts the cost and potential income of the second mission.

The third automated mission demonstrates the ability to use lunar-produced oxygen as propellant to return an OTV lander to LEO with 8000 kg of lunar material payload. The payload to the Moon for this third mission is a much larger LOX propellant production plant and the LH_2 fuel and an aerodynamic braking shield for the return flight to LEO. Table 9 shows the third mission's activities. Although the revenues for these missions are derived largely from entertainment and trinket sources, if adequate markets exist, such missions could prove critical technologies, including lunar teleoperation, chemical and physical processing, and lunar propellant handling. The permanent lunar surface node group (E. Bock, J. Burke, L. Snively, and B. Tillotson) explored a range of private activities that could produce goods and services at a profit at that location. These could include provision of a turnkey lunar base or support for an existing base with life support, power, communications, teleoperations, landing facilities, storage, propellant supply, or food and supply cache and placement. Off-base markets could also include construction services to build private facilities, large antennas, scientific arrays, and rescue and emergency support services. The group also assessed the required components for such a lunar surface node and estimated current development stages for each (see Table 10).

TABLE 7. Mission I scenario.

Expend (soft land) OTV second stage on lunar surface.	
Leave OTV first stage in lunar orbit.	
Assume 10-tonne payload (direct from LEO).	
Payload (tonnes)	
Pilot LOX production plant	2.00
Six teleoperated lunar rovers	4.00
TV cameras and transmitter	
End effector	
Mech/electrostatic beneficiator	
Core TV and Earth transmitter	1.00
Core payload structure/avionics	3.00
	10.00
Cost ($ million)	
Development	
Payload core	20.00
Pilot LOX plant	20.00
Lunar rovers	0*
OTV/Lunar lander (expended)	40.00
Insurance	20.00
Total development	100.00
Transportation ($11,000/kg)	100.00
Total	200.00
Mission	
Lunar rover race (entertainment)	
Lunar product advertising	
Surface survey (materials)	
Iron and glass collection	
LOX production demonstration	
Collect unusual lunar surface samples	
Income ($ million)	
Sponsorship of lunar rovers by major automobile company ($20m × 6)	120.00
Subsponsor of rovers by auto equip. suppliers ($2m × 3 × 6)	36.00
Exclusive TV rights to race	20.00
Advertising during race	20.00
Marketing franchises	20.00
Filming rights	50.00
Fee to drive rovers on survey trips	2.00
Survey TV coverage	2.00
Advertising during survey coverage	5.00
Doc. of project (book/movie rights)	1.00
Gambling commission on lunar race	10.00
Total income	286.00
Schedule (years)	
Development	1-3
Production	3, 4
Launch	5
Payback	5

*Funded by sponsors.

LUNAR RESOURCES AND MANUFACTURING

The lunar processing and manufacturing subgroup (J. Burke, A. Cutler, R. Ness, S. Vetter, and G. Woodcock) examined products that could be manufactured at the lunar surface or at a space manufacturing facility, assumed for purposes of this study to be colocated with a mass catcher at libration point L2. Table 11 shows six classes of initial products that could be made from lunar resources. This figure also shows the feedstock materials necessary to produce them. Woodcock proposed that an examination of a LOX LH_2, fuel cell-based power storage system, which would

TABLE 8. Mission II scenario.

Expend (soft land) OTV on lunar surface.	
Assume 10-tonne payload (direct from LEO).	
Payload (tonnes)	
Second generation LOX plant	3.00
Iron coin sintering equipment	1.00
Glass processing equipment	1.00
Return rocket for high value payload	5.00
	10.00
Cost ($ million)	
OTV/lunar lander (expended)	40.00
Development	
Payload core	10.00
LOX plant	20.00
Iron minting	5.00
Glass processing	5.00
Insurance	20.00
	100.00
Transportation ($11,000/kg)	100.00
	200.00
Mission	
Coin production from lunar materials	
Lunar glass jewelry production	
LOX production	
Return coins and jewelry to LEO	
Return unusual lunar samples	
Income ($ million)	
Return 1.5 tonnes of lunar material with value (when properly packaged) of $500/carat	750.00

TABLE 9. Mission III scenario.

Payload (tonnes)	
(UP) third generation LOX plant	6.00
LH_2 propellant and tankage	2.00
Aerobreak	2.00
	10.00
(Down) aerobreak	2.00
Lunar material/products	8.00
	10.00
Cost ($ million)	
OTV (expended)	30.00
LH_2 payload	2.00
Aerobreak	8.00
Third generation LOX plant	40.00
Insurance	20.00
Transportation	100.00
	200.00
Income	
Return 8 tonnes of lunar material with value of $200/carat	1600
Mission	
Land OTV with payload that includes	
Aerobrake for return to LEO	
Hydrogen propellant and tankage	
Third generation LOX production plant	
Transfer third generation LOX production plant to first OTV	
Fill newly landed OTV with LOX from earlier OTV/propellant plants	
Return newly landed OTV with 8 tonnes of lunar material payload to LEO	

Subsequent missions ready to supply LOX for manned missions.

TABLE 10. Lunar surface node requirements.

Component	Intitial Source			Later Source			Development Stage*
	Earth	Space	Lunar	Earth	Space	Lunar	
Mass Driver	x			x		x	D
Construction/Assembly							
Crew (2+ for safety)	x			x			M
Intermittent Habitat							
Shielding (Dirt)			x			x	E
Consumables	x			x	x	x	D
Waste Reuse	x			x		x	D
EVA Suits	x			x			C
Vehicles	x			x			D
Landing Site							
Landing Pad			x			x	C
Beacon	x			x			E
Blast Shield			x			x	D
Refueling	x					x	C
Teleoperations	x			x		x	M/E
Spare Parts	x			x	x	x	—
Recharger	x			x		x	M/E
Comm links	x			x			M
Garage	x		x			x	E
Service and Repair	same requirements as assembly, above						
Power							
SP-100 or equiv.	x			x			D
Solar	x		x		x	x	C
Storage	x			x	x	x	C
Material Collector	x			x		x	D

* Key to development stages: Mature (M): production hardware is available off-the-shelf; Engineering (E): preproduction prototypes tested and in use; Development (D): operational prototype underway; Conceptual (C): idea with some theoretical support.

This table shows the parts needed for manned operations on the lunar surface. It shows the source of the initial supply of the component, and estimates where the later supply source. The final column gives an estimate of the state of the engineering for the component.

double as an oxygen production plant, would be a key production component (Fig. 7). The consensus of the group was that a good analysis of solar power and power storage options is an important tool for decision making about nuclear, solar, or other power generation options. Woodcock outlined the design and buildup sequence of a production facility that could produce 250,000 kg of LOX per year (Table 12). The ground rule for the facility was to run the production plant at at least 50% of its rating at night to avoid shut-down and attendant system damage. This equated into a 2-MW daytime power requirement for the plant and a 500-kW night requirement. To store the requisite 10^5 kWhr of energy would require approximately 40,000 kg of O_2 and 5000 kg of H_2 as fuel cell reactants. A 2-MW photovoltaic power array would provide 1 MW of power for daytime use and 1 MW of storage charging power. The mass budget for the plant would be 140,000 kg made up of solar collectors (40,000 kg), power conditioning (10,000 kg), storage tanks (45,000 kg), and reactants (45,000 kg). Since 40,000 kg of the reactant mass is O_2 and may be lunar derived, this requires a 120,000-kg delivery from the Earth. Table 12 depicts a buildup sequence for this facility and assumes that a Mass-Driver is used to export the oxygen to a libration point tank farm for eventual delivery to LEO.

TABLE 11. Initial lunar product categories.

	Iron	O_2	Soil	Glass
Power Generation		x		
Radiators	x	x		
Pressure Vessels	x			x
Propellant		x		
Shielding	x		x	
Structures	x			x

TABLE 12. Buildup sequence for LOX facility (at 20 tonnes per delivery).

1:	125 kW power module (no storage)
2:	Deliver 1/2 of reactant tanks
3:	Pilot O_2 production module (capacity 0.6 tonnes/week = 30 tonnes/year)
4:	Deliver 300-kW power module
5:	Deliver O_2 production module
6-9:	Four trips to grow to 250 tonnes/year
10-17:	Deliver lunar base (government option)
18-20:	Deliver 150 tonnes/year Mass Driver
21-22:	Deliver 200-tonne capacity tank farm to 1.2

During steps 1-5 spent landers provide 25 tonnes of storage capacity.

Another major emphasis of the production group was the utility of using iron from lunar regolith as a feedstock for space manufacturing. Iron exists in relatively pure form as a result of meteoric bombardment. Work by Agosto (*Agosto,* 1981) and others indicates that magnetic and electrostatic beneficiation may be suitable to provide fine iron powder without chemical processing. In addition to powdered metallurgy, common terrestrial iron processing techniques can be employed to make a wide variety of useful products from this common metal.

MISCELLANEOUS AREAS

In addition to the nodes previously described, Dani Eder outlined an air-launched system that could launch material into LEO for approximately $1000/kg. He also showed a tethered spaceport consisting of a landing platform at orbital altitude, but at less than orbital velocity. This is made possible by connecting the platform to a balast mass made of nonterrestrial materials (Fig. 8).

OVERALL IMPLEMENTATION

Figure 9 details the overall implementation scenario. Emphasis is on automated or teleoperated systems wherever possible, with the expectation that repair and maintenance will be performed with some on-site human assistance (E. Bock and B. Tumlinson).

CONCLUSION

The 1988 Lunar Systems Workshop continued the trend followed in the 1978 and 1980 evolutions of nonterrestrial materials system design toward smaller and less expensive implementations. Economic viability is the key to the growth and health of space systems, just as in terrestrial projects.

Market information is critical to economic analysis of space systems. Our group found that assessing market values of the systems was actually more difficult than addressing technical issues. Not surprisingly, market figures for activity closer in distance to the Earth and closer in time to the present are more accurate than those for lunar surface systems or those systems that will follow lunar systems operations.

Government can do two important things to accelerate the growth of space manufacturing systems. The first of these is to develop the required transportation infrastructure. Government

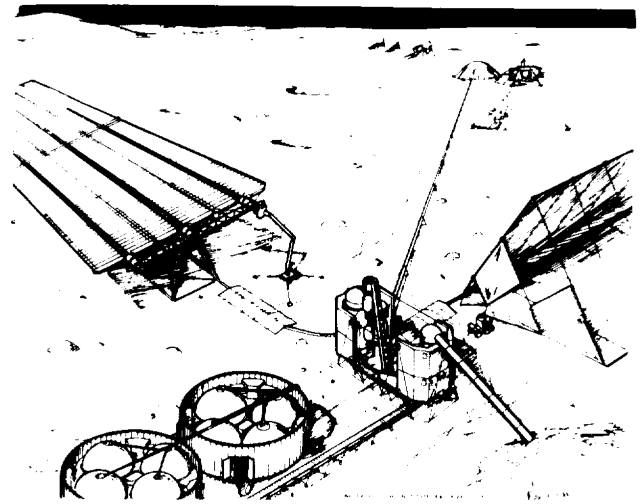


Fig. 7. Lunar oxygen production facility.

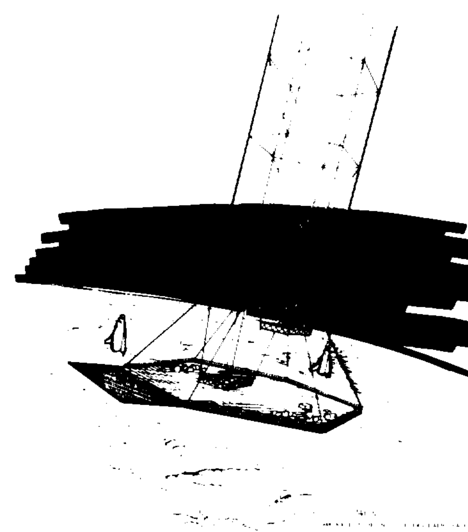


Fig. 8. Tethered LEO spaceport.

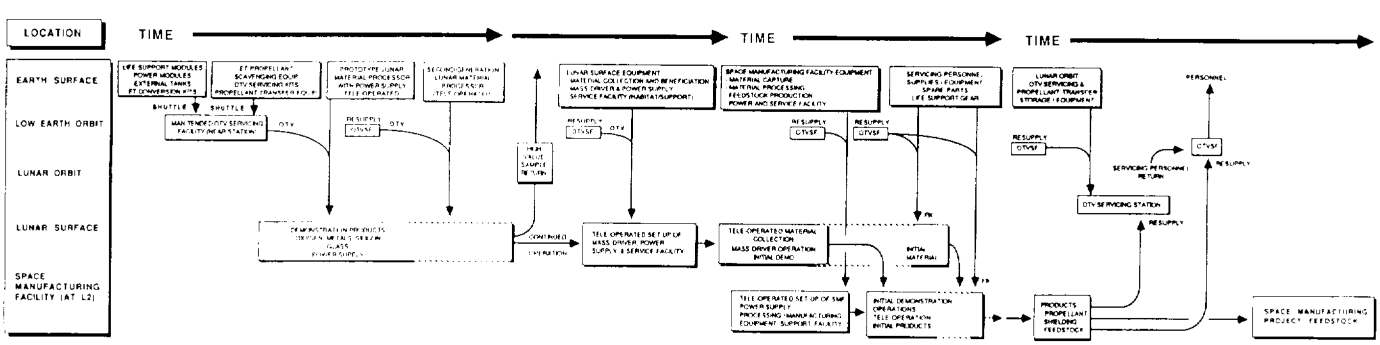


Fig. 9. NTM infrastructure timeline. This implementation scenario was authored by E. Bock and drawn by R. Tumlinson.

can also guarantee markets for commodities and manufactured products. If the markets are there, technical expertise and capital funds exist to address market needs.

Acknowledgments. The 1988 Space Studies Institute Lunar Systems Workshop was sponsored by a contract from the Martin Marietta Corporation. Support for workshop participants came from Boeing Aerospace and General Dynamics Corporation. Special thanks to Eagle Engineering and the Space Frontier Society who sponsored the attendance of P. Rawlings. His visualizations of the conference efforts are greatly appreciated. The workshop was hosted by GE Astro Space Division in East Windsor, New Jersey.

REFERENCES

Agosto W. (1981) Beneficiation and powder metallurgical processing of lunar soil metal. *Space Manufacturing, 4,* 365-370. AIAA, New York.

Andrews D. G. and Snow W. R. (1981) The supply of lunar oxygen to low Earth orbit. *Space Manufacturing, 4,* 173-179. AIAA, New York.

Billingham J. and Gilbreath W., eds. (1979) *Space Resources and Space Settlements.* NASA SP-428, Washington, DC. 288 pp.

Bock E. (1979) Lunar resources utilization for space construction. *NAS-9-15560.* DRL-T-1451, NASA Johnson Space Center, Houston, GD/Convair Contractor Report.

Brown W. C. (1987a) A microwave powered orbiting industrial park system. *Space Manufacturing, 6: Nonterrestrial Resources, Biosciences, and Space Engineering,* pp. 242-250. Washington, DC.

Brown W. C. (1987b) LEO to GEO transportation system combining electric propulsion with beamed microwave power from Earth. In *Papers Presented at the Goddard Memorial Symposium.*

Johnson R. D., ed. (1979) *Space Settlements: A Design Study.* NASA SP-413, Washington, DC.

Miller R. H. and Smith D. (1979) *Extraterrestrial Processing and Manufacturing of Large Space Systems.* CR-161293, NASA Marshall Space Flight Center, Huntsville, Alabama.

National Research Council (1981) *Electric Power from Orbit: A Critique of a Satellite Power System.* National Academy of Sciences, Washington, DC.

O'Neill G. K. (1974) The colonization of space. *Phys. Today, 27,* 32-40.

O'Neill G. K. (1978) *The Low (Profile) Road to Space Manufacturing,* pp. 24-32. AIAA, New York.

O'Neill G. K. and O'Leary B., eds. (1977) *Space-Based Manufacturing from Nonterrestrial Materials,* Vol. 57, pp. 3-18. AIAA, New York.

O'Neill G. K., Driggers G., and O'Leary B. (1980) New routes to manufacturing in space. *Astronaut. Aeronaut., 18,* 46-51.

Sercel J. C. (1986) *Beamed Energy for Spacecraft Propulsion.* Space Studies Institute, Princeton, New Jersey.

Space Research Associates (1985) *Solar Power Satellite Built of Lunar Materials.* Space Studies Institute, Princeton, New Jersey. 98 pp.

U.S. Department of Energy (1980) *Final Proceedings of the Solar Power Satellite Progam Review.* CONF-800491, Lincoln, NB. NTIS, Springfield, Virginia.

Waldron R. D. (1985) Total separation and refinement of lunar soils by the HF acid leach process. *Space Manufacturing, 5: Engineering With Lunar and Asteroidal Materials,* pp. 132-149. AIAA, New York.

Woodcock G. (1988) Basing options for lunar oxygen for manned Mars missions. In *Papers Presented at the Space 1988 Conference,* pp. 420-434. Albuquerque, New Mexico.

LUNAR RESOURCE RECOVERY: A DEFINITION OF REQUIREMENTS

N93-1 978

D. Elsworth, J. L. Kohler, and S. S. Alexander

College of Earth and Mineral Sciences
Pennsylvania State University
University Park PA 16802

The capability to locate, mine, and process the natural resources of the Moon will be an essential requirement for lunar base development and operation. The list of materials that will be necessary is extensive and ranges from oxygen and hydrogen for fuel and life support to process tailings for emplacement over habitats. Despite the resource need, little is known about methodologies that might be suitable for utilizing lunar resources. This paper examines some of the requirements and constraints for resource recovery and identifies key areas of research needed to locate, mine, and process extraterrestrial natural resources.

INTRODUCTION

Exploration and settlement of the solar system is an integral part of the civilian space agenda (*National Commission on Space*, 1986; *Ride*, 1987). Included in this agenda is the establishment of intermediate bases to satisfy immediate goals, as well as to facilitate other long-term targets (*Duke et al.*, 1985). Implementation and attainment of these goals is heavily dependent on the ability to exploit extraterrestrial natural resources.

The energy required to transport resources from Earth to high-Earth orbit is almost 20 times greater than that required to transport the same mass from the lunar surface. The associated transportation costs alone effectively preclude transporting the necessary resources from Earth. Given the resource-rich bodies of the Moon and those beyond, a viable alternative can be envisioned. A technology base must be developed to facilitate exploitation of existing extraterrestrial resources. Although the experience and even some of the components of terrestrial mining and processing systems may be adapted and used extraterrestrially, the aggressive lunar environment will likely force consideration of unique solutions to unique problems. The highly evacuated, low gravitational, cosmically bombarded lunar environment, subject to massive temperature swings, presents untold challenges and hardships in terms of mere daily survival. Superimposing on this regimen the hardships and risks associated with mining, reputedly one of the most hazardous endeavors in the terrestrial environment, is indeed a challenge.

CONSIDERATIONS FOR RESOURCE RECOVERY

The successful utilization of extraterrestrial resources requires access to reserves of suitable concentration and quantity to facilitate timely and economic recovery. One result of the Apollo legacy is a baseline knowledge of the abundant lunar resources. Oxygen-rich minerals in the regolith could be mined and processed to satisfy six-sevenths of the need for rocket fuel. It may even be possible to extract sufficient hydrogen to supply the remaining one-seventh of the fuel (*Carter*, 1985; *Friedlander*, 1985). Other fundamental uses of the materials would be to manufacture water and a habitable atmosphere. Even the unprocessed regolith would be useful as propellant for mass-driver engines, as a shielding material to cover habitats (*Kaplicky and Nixon*, 1985), and for soilless media for agriculture. Water may be available within the regolith located close to polar regions where it may remain locked as ice (*Arnold*, 1979). Alternatively, manufactured forms are available from alkalai-hydroxide-based schemes (*Cutler*, 1984) or from hydrogen reduction of ilmenite (*Agosto*, 1985). To catalyze the processes, initial supplies of hydrogen may have to be transported directly to a lunar base as liquefied hydrogen, methane, or ammonia; alternatively, it could be produced by microwave bombardment (*Tucker et al.*, 1985) or microbial processing of the regolith (*White and Hirsch*, 1985).

The integrated systems approach to the problem of extraterrestrial resource recovery is illustrated in Fig. 1. The research effort must be driven by resource needs, such as ilmenite or habitable space. Lunar resource recovery is an essential but supporting operation to NASA's mission objectives; as such, resource recovery strategies must be commensurate with these objectives. Given the mission objectives and available information on lunar geology and ore, it is first necessary to develop integrated systems concepts for resource recovery.

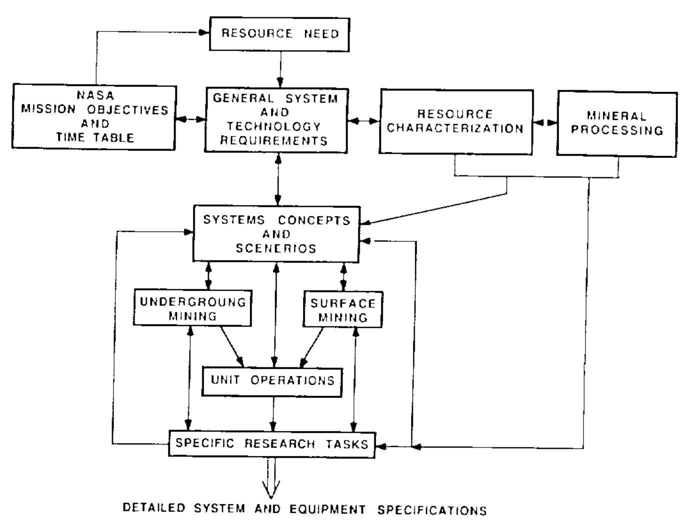


Fig. 1. Systems approach to lunar resource recovery.

RESOURCE REQUIREMENTS

Resource requirements consist of materials required to construct, operate, and sustain a permanent base and to satisfy deep space exploration and space-based manufacturing. The list of required raw materials is long. Of these, oxygen and hydrogen are of paramount importance, not only because of their use in recyclable forms necessary for the life-support systems but also in expendable rocket fuels. Other carbon-based gases must be sought if any lunar-based agriculture is contemplated together with iron, silicon, titanium, manganese, and other metals to support product manufacture.

While ilmenite is the most obvious and important mineral to locate and extract in quantities sufficient to supply oxygen needs on the Moon, other minerals may be exploited as well, if found in sufficient quantities. These include the following: anorthite ($CaAl_2Si_2O_8$), from which aluminum and oxygen could be extracted; pyroxene ($MgFeSi_2O_6$), from which magnesium, iron, and oxygen could be extracted; and minerals associated with layered mafic complexes that would yield copper, platinum, nickel, cobalt, and sulfides. Anorthite is known to be abundant in the lunar highlands, pyroxene in the mare regions, and layered mafic complexes possibly exist in the large, impact-generated mare regions. In addition, the various sites where transient lunar phenomena (TLMs) have been observed should be investigated as potential sources of water, carbon dioxide, carbon monoxide, and methane; they tend to be associated with the boundaries of the larger mare.

It has been established that oxygen can be obtained through a reduction process of ilmenite (*Simon,* 1985; *Gibson and Knudsen,* 1985), an apparently abundant lunar resource. The recovery of "solar wind trapped hydrogen" in lunar soils is more speculative (*Carter,* 1985), but should be considered as part of the extraction process for other ores. Any beneficiation operation of lunar regolith for ilmenite should also address the feasibility of recovering hydrogen, as well as suitable treatment of the tailings for use in local construction or agricultural purposes.

Habitable space must also be available to support lunar activities. Prefabricated and regolith-shielded structures (*Land,* 1985) may be the method of choice, although novel techniques utilizing traditional cements (*Lin,* 1985) or hybrid ceramic derivatives (*Young,* 1985; *Khalili,* 1985) have potential. Regolith burial offers protection from high external radiation levels but leaves structures susceptible to micrometeorite impact (*Gehring,* 1970). Deeper basing in lava tubes (*Hörz,* 1985) or remnant-mined cavities offers protection from hypervelocity impacts and the possibility of providing, to a certain degree, controlled habitable environments with reduced diurnal temperature swings.

The severity of the economic constraints applied to lunar basing and attendant mining operations depend primarily on the perceived utility of the effort. If the establishment of a base and the development of an associated mineral extraction and processing capability is perceived primarily as an issue of geopolitical prestige and strategic importance, economic concerns may not be paramount. However, many different engineering and scientific studies must compete for finite resources, in which case relative allocations among disciplines must be determined by current priorities. To provide a clear justification for propellant manufacture on the lunar surface, it is conceivable that lunar production will at some stage be subject to comparisons with delivered costs from the Earth's surface. In the case that lunar production is unable to compete directly with that from Earth, the shortfall may be justified on the grounds that lunar prototypes may be used directly to develop propellant manufacture on more distant planets. Production of high payback ratio products such as He^3 from the lunar surface may, however, completely defray the production costs required in the production of propellant from ilmenite.

EXPLORATION CONSTRAINTS

Three crucial areas may be identified representing *exploration, mining,* and *mineral processing* activities. Initially it will be necessary to utilize the lunar soils for resources as a lunar base is becoming established. Over time, however, it will be desirable to locate other and more concentrated deposits. The need for resources not found in the lunar soils will also impose a requirement to locate currently unknown deposits. Thus it will be necessary to develop suitable prospecting techniques to satisfy these needs and to characterize the materials *in situ* prior to mining and mineral processing.

During the initial phase, remote sensing and other synoptic exploration methods would be used to identify the most suitable candidate sites for a base. Ilmenite concentration, regolith morphology, and size distribution of ilmenite-bearing rocks, together with geographic location, would be the criteria used in site selection. As the base progressively develops, it can be anticipated that the simplistic surface mining of regolith will become increasingly undesirable due to the large investment of time and energy required to extract relatively little ilmenite. Given the prospects for finding much higher concentrations, efforts will be required to locate these deposits. Once located, the ore bodies must be characterized prior to mining. It is likely that the higher grade deposits in bedrock will probably consist of differentiated lava flows or sills and will require underground mining. While an underground operation will be decidedly more complex than a surface one, there will be inherent benefits to offset the increased complexity. A byproduct of the underground operation will be environmentally controlled space, which might be used for habitation, storage, or emplacement of nuclear reactors. An underground operation will probably offer other economies as a centralized mining and processing center, developed with years of potential reserves. It may even be desirable to "mine" solely for the purpose of creating habitable space in certain locations. Although the creation of a habitable structure through mining would represent a radical departure from the "turn-key" approach, it would eliminate many difficult problems associated with Earth-based delivery and erection of habitats.

MINERAL EXTRACTION CONSTRAINTS

The development of innovative mining methods and equipment offers the strongest possibilities of technological gain in autonomous resource exploitation. The development of innovative mining systems and equipment that will meet the mission objectives will require an integrated examination of the overall system, including the pre- and postmining activities of exploration and mineral processing.

Ore extraction requires knowledge of various rock and rock mass properties, including those of the ore. This information is necessary to extract the material and is needed to make ancillary decisions such as those related to stability and artificial support. Currently, these parameters are determined through manual measurements. Thus, developments in the areas of intelligent signal processing of computer vision signals, ground-penetrating

radars, and microseismic techniques, among others, will be needed to support resource extraction.

Excavation and extraction within the hostile and dangerous underground mining environment are prime contenders for the development of autonomous and teleoperated equipment. Autonomous mining machines must have an inherent capability to detect incipient failure; a self-repair capability is also desirable. Monitoring and signal-processing methods designed to identify fundamental deterioration mechanisms in the electrical, mechanical, and hydraulic systems are desirable adjuncts to autonomous vehicle operation and will be necessary to allow early detection of incipient failures. Improved methods of horizon and interface sensing and guidance control are also mandated if practical application of autonomous equipment is envisioned. Pattern recognition and expert system approaches are both under investigation and development.

The development of efficient methods of rock fragmentation is crucial to the success of lunar mining operations. The behaviors associated with rock fragmentation (*Trent,* 1977) and strength (*Johnson et al.,* 1973; *Carrier et al.,* 1973) will be different due to environmental factors such as the hard vacuum and anhydrous conditions (*Williams and Jadwick,* 1980). Most terrestrial mining systems use either mechanical cutting or blasting. Mechanical cutting as a principal winning mechanism can be deemed undesirable on the Moon, based on the anticipated lubrication and tribology problems. Because of these problems, the life of a continuous mining machine or tunnel borer might be unacceptably low.

A modified boring machine, using thermal rather than mechanical penetration, has been proposed (*Rowley and Neudecker,* 1985); however, preliminary calculations suggest that its energy requirements would be prohibitively large. Mechanical drill penetration is known to be problematic in lunar regolith due to clogging and vacuum adhesion problems (*Podnieks and Roepke,* 1985; *Blacic,* 1985), and alternatives are sought. Jet piercing would not be practical in a location where oxygen is not plentiful; however, other thermal penetration methods might be viable (*Thirumalai and Demou,* 1970; *Lindroth,* 1974). The *in situ* melting concept might be better adapted to produce small diameter blast holes rather than large diameter tunnels. If a satisfactory means of creating the holes can be developed, the innate advantages of blasting could be available. This alternative may prove fertile since it is also known that explosives will work in a hard vacuum.

Of particular interest are the strength and abrasion resistance properties of fractured granular media and rock in the lunar vacuum. Laboratory and micromechanical models used to describe behavior will be key to the development of rock excavation, penetration, handling, and breakage, together with the feasibility of *in situ* processing. Fundamental understanding of the *in situ* strength is necessary in the dimensioning of excavations formed during mineral extraction and utilized as pressurized habitable space.

Electrical energy production with appropriate failsafe and backup capabilities is necessary to ensure an uninterrupted supply for life support. Requirements of several kilowatts for the maintenance of a habitable environment will be greatly exceeded by the demands placed by a significant mineral extraction and processing operation. Although life support requirements may be met by solar energy (photovoltaic), yields of the order obtainable only from nuclear plants will be required for mining and manufacturing operations. Continuous outputs from regolith-shielded nuclear units suggest the utility of round-the-clock mining operations in the absence of easily utilized energy storage mechanisms. Excess thermal energy from these units could be used in the habitable environment or in material processing.

MINERAL PROCESSING CONSTRAINTS

Processing of ores in the low gravity and evacuated lunar environment requires the adoption of special approaches to mineral comminution and separation problems. Breakage and size reduction issues may be addressed in studies of ball mill centripetal comminution processes. Generic mineral and ilmenite reduction processes may also be approached using electrostatic, nonaqueous, liquid-liquid, and pyroprocessing methods. Individual components of these studies may best be addressed in separate multidisciplinary research efforts.

SUMMARY

The successful recovery of the necessary materials from lunar resources will require the capability to locate, mine, and process the available natural resources. Much of the technology to achieve this is as yet undeveloped. The tightly interrelated nature of exploration, mining, and processing dictates that necessary research and development work be undertaken with this in mind. An integrated systems approach is necessary. Similarly, equipment development must be completed to satisfy the exploration, mining, and processing needs, rather than constraining candidate methodologies for exploration, mining, and processing to the capabilities of developed equipment.

While it will be necessary to develop innovative and new solutions to the lunar resource recovery problem, the knowledge base of terrestrial mining provides a wealth of information that is directly applicable to lunar exploration and mining. Current research in terrestrial resource recovery, such as *in situ* resource characterization and autonomous mining, will have application in the lunar setting. In a complementary manner, specific advancements required to facilitate lunar mining should provide a significant benefit in terrestrial resource recovery.

Acknowledgments. The previous represents partial results from a project on "Intelligent signal processing applied to autonomous resource recovery" sponsored by the Mine Safety Appliance Company. The endowment is administered by the College of Earth and Mineral Sciences of the Pennsylvania State University. This support is gratefully acknowledged. The evolution of concepts presented in this manuscript has benefitted from the comments of our colleagues J. A. Dutton, D. P. Gold, J. Louie, and P. T. Luckie.

REFERENCES

Agosto W. N. (1985) Electrostatic concentration of lunar soil minerals. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 453-464. Lunar and Planetary Institute, Houston.

Arnold J. R. (1979) Ice in the lunar polar regions. *J. Geophys. Res., 84,* 5659-5668.

Blacic J. D. (1985) Mechanical properties of lunar materials under anhydrous, hard vacuum conditions: Application of lunar gas structural components. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 487-495. Lunar and Planetary Institute, Houston.

Carrier W. D., Bromwell L. G., and Martin R. T. (1973) Behavior of returned lunar soil in vacuum. *J. Soil Mech. Div., ASCE,* 979-996.

Carter J. L. (1985) Lunar regolith fines: A source of hydrogen. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 571-581. Lunar and Planetary Institute, Houston.

Cutler A. H. (1984) An alkali hydroxide based scheme for lunar oxygen production (abstract). In *Papers Presented to the 1984 Symposium on Lunar Bases and Space Activities of the 21st Century,* p. 21. NASA Johnson Space Center, Houston.

Duke M. B., Mendell W. W., and Roberts B. B. (1985) Towards a lunar base programme. *Space Policy, 1,* 49-61.

Friedlander H. N. (1985) An analysis of alternate hydrogen sources for lunar manufacture. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 611-618. Lunar and Planetary Institute, Houston.

Gehring J. W. Jr. (1970) Engineering considerations in hypervelocity impact. In *High Velocity Impact Phenomena* (R. Kinslow, ed.), pp. 463-514. Academic, New York.

Gibson M. A. and Knudsen C. W. (1985) Lunar oxygen production from ilmenite. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 543-550. Lunar and Planetary Institute, Houston.

Hörz F. (1985) Lava tubes: Potential shelters for habitats. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 405-412. Lunar and Planetary Institute, Houston.

Johnson B. V., Roepke W. W., and Strebig K. C. (1973) Shear testing of simulated lunar soil in ultra high vacuum. *RI 7814,* pp. 1-18. Bureau of Mines, Washington.

Kaplicky J. and Nixon D. (1985) A surface-assembled superstructure envelope system to support regolith mass-shielding for an initial-operational-capacity lunar base. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 375-380. Lunar and Planetary Institute, Houston.

Khalili E. N. (1985) Magma, ceramic, and fused adobe structures generated *in situ.* In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 399-403. Lunar and Planetary Institute, Houston.

Land P. (1985) Lunar base design. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 363-373. Lunar and Planetary Institute, Houston.

Lin T. D. (1985) Concrete for lunar base construction. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 381-390. Lunar and Planetary Institute, Houston.

Lindroth D. P. (1974) Thermal diffusivity of six igneous rocks at elevated temperatures and reduced pressures. *RI 7954,* pp. 1-33. Bureau of Mines, Washington.

National Commission on Space (1986) *Pioneering the Space Frontier.* Bantam, New York. 211 pp.

Podnieks E. R. and Roepke W. W. (1985) Mining for lunar base support. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 445-452. Lunar and Planetary Institute, Houston.

Ride S. K. (1987) *Leadership and America's Future in Space: A Report to the Administrator.* U.S. Govt. Printing Office, Washington, DC. 63 pp.

Rowley J. C. and Neudecker J. W. (1985) *In situ* rock melting applied to lunar base construction and for exploration drilling and coring on the Moon. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 465-477. Lunar and Planetary Institute, Houston.

Simon M. C. (1985) A parametric analysis of lunar oxygen production. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 531-541. Lunar and Planetary Institute, Houston.

Thirumalai K. and Demou S. G. (1970) Effect of reduced pressure on thermal expansion behavior of rocks and its significance to thermal fragmentation. *J. Appl. Phys., 41,* 5147-5151.

Trent M. E. (1977) *Metal Cutting.* Butler and Tanner, London. 203 pp.

Tucker D. S., Vaniman D. T., Anderson J. L., Clinard F. W. Jr., Feber R. C. Jr., Frost H. M., Meed T. T., and Wallace T. C. (1985) Hydrogen recovery from extraterrestrial materials using microwave energy. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 583-590. Lunar and Planetary Institute, Houston.

White D. C. and Hirsch P. (1985) Microbial extraction of hydrogen from lunar dust. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 591-206. Lunar and Planetary Institute, Houston.

Williams R. J. and Jadwick J. J. (1980) *Handbook of Lunar Materials.* NASA RP-1057, pp. 113-116. NASA Johnson Space Center, Houston.

Young F. J. (1985) Concrete and other cement-based composites for lunar base construction. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 391-397. Lunar and Planetary Institute, Houston.

ELECTROLYTIC SMELTING OF LUNAR ROCK FOR OXYGEN, IRON, AND SILICON

Larry A. Haskin, Russell O. Colson, David J. Lindstrom[1], Robert H. Lewis[2], and Krystyna W. Semkow[3]

Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences
Washington University
St. Louis MO 63130

Preliminary studies of the electrochemical properties of silicate melts such as those available from heating of lunar mare soils indicate that conductivities are high enough for design of a practical electrolytic cell. The nature and kinetics of the electrode reactions, which involve reduction of Fe^{2+} and Si(IV) and oxidation of silicate anions as the primary, product-forming reactions, are also satisfactory. A survey of the efficiencies for production (amount of product for a given current) of O_2, Fe^0, and Si^0 as functions of potential and of electrolyte composition indicate that conditions can be chosen to yield high production efficiencies. We also conclude that electronic conductivity does not occur to a significant extent. Based on these data, a cell with electrodes of $30\ m^2$ in area operating between 1 and 5 V with a current between 1.6 and 3.5×10^5 A for a mean power requirement of 0.54 MW and total energy use of ~13 MWhr per 24-hr day would produce 1 tonne of O_2, 0.81 tonne of Fe^0, 0.65 tonne of Si^0 (as Fe^0-Si^0 alloy), and about 3.5 tonnes of silicate melt of altered composition per 24 hr. Adjustable distance between electrodes could offer flexibility with respect to feedstock and power source.

INTRODUCTION

As the breadth of activities in near-Earth space increases, we will need increasing amounts of materials for use there. Because of Earth's substantial gravitational well, the ratio of payload delivered per unit of launch energy is rather low, even for hauling materials to low-Earth orbit (LEO) (300-500 km). The Moon has only one-sixth the gravity of Earth, and a given amount of energy will boost many times as much payload from the surface of the Moon to LEO as from the surface of Earth to LEO. Because the cost of each launch from Earth is high, it is possible that the Moon could be a cheaper source than the Earth for bulky, relatively unspecialized materials for use in space. Comparisons must include the combined costs of mining, smelting, manufacturing, and transporting the nonterrestrial material.

One material we expect to need in increasing quantities in LEO is oxygen, mainly for use as the oxidizer in propellant. We might be able to supply oxygen economically from the Moon for use in LEO. Oxygen is the most abundant element in the lunar regolith, where it occurs in chemical combination with metallic elements (*Haskin and Warren,* 1991). There remains the possibility that water, another potential source of oxygen, will be found at the lunar poles (*Arnold,* 1979; *Lanzerotti and Brown,* 1981), but we ignore that possibility here.

Other bodies with even lower gravity than the Moon are also potential sources of oxygen for use in LEO. However, we cannot at this time estimate accurately the economics of providing oxygen from Phobos, Deimos, or a near-Earth asteroid relative to lunar oxygen or terrestrial oxygen. While we have theoretical reasons to believe that some asteroids and possibly the satellites of Mars may have water bound in their minerals, we have not verified the presence of such water by direct observation. We do not know the natures of the regoliths of these bodies or how to mine them. (We know little enough about how to mine the Moon.) We do not know how much more difficult mining and extraction might be on bodies with nearly zero gravity than on the Moon with its one-sixth gravity. For now, the only extraterrestrial materials that we know enough about to plan in some detail to use are those abundant materials whose chemical and physical characteristics and setting we know, namely, the lunar soils and, at Hadley Rille, mare basalts. We note that there is currently no means to transport mining and extraction apparatus from Earth to either the Moon or the other bodies.

We believe the Moon, because of its proximity and because of our knowledge of its regolith, is the most sensibly accessible source of significant amounts of extraterrestrial material for the near future. Furthermore, it may be feasible to extract hydrogen for use as a propellant, so both fuel and oxidizer can be furnished for use on the Moon and in LEO (*Haskin,* 1991). Although the Moon apparently accreted very low initial concentrations of volatile materials such as water and carbon compounds, and even if it does not have abundant polar water *per se,* its soils contain large quantities (albeit at very low concentrations) of hydrogen, carbon, nitrogen, and noble gases of solar wind origin.

The purpose of this paper is to add to our understanding of how lunar material might be used as a source of oxygen. In particular, we report results of experiments on electrolysis as a means of producing oxygen, metals, and silicates of altered composition. Electrolysis is well suited to lunar conditions in the sense that it does not require an extensive set of companion processes to produce specialized reagents or materials present in Earth's environment but absent on the Moon. It does not require a continuous supply of materials from Earth. It does not require water for use as a cheap extracting agent or cooling agent, or air to serve as an oxidizing agent or cooling agent. It does not require terrestrial reagents such as wood, coal, or even limestone, nor does it require prepared chemicals to serve as reagents or

[1] Now at Mail Code SN2, NASA Johnson Space Center, Houston TX 77058
[2] Now at GE Astro Space Division, P.O. Box 800, Princeton NJ 08543-0800
[3] Now at Department T40, IBM Corp., Box 8003, 1701 North Street, Endicott NY 13760

feedstocks. It will not be compromised by the Moon's strong vacuum and should not be strongly affected by its low gravity. It requires only heat, electrical power, and a suitable electrolytic cell. It can use a relatively unspecialized feedstock such as finely pulverized lunar soil, and can make use of available sunlight for heat and electrical power.

We have begun laboratory bench-scale testing to determine whether electrolysis of molten lunar soil or rock should be further considered as a viable process for smelting on the Moon to yield oxygen gas and iron and silicon metals. Our approach is to understand the fundamental electrochemcial properties of silicate melts and to estimate from them the parameters of an electrolytic separation system. In particular, we have adapted well understood procedures for voltammetry and chronopotentiometry and applied them to silicate melts at high temperatures, and have identified the competing anodic and cathodic reactions (*Semkow et al,* 1982; *Semkow and Haskin,* 1985). We have measured conductivities of simulated lunar silicates. We have made a preliminary determination of the efficiency for the reduction of Fe^{2+} and Si(IV) to metal. We have evaluated the possibility that transition metal silicates conduct electronically. We have measured efficiencies for production of O_2 as functions of the partial pressure of oxygen surrounding the melt (fO_2), electrode potential, and melt composition. Finally, we have made first-cut estimates of the operating parameters for a producing electrolytic cell.

ELECTRODE REACTIONS

While previous studies (*Oppenheim,* 1968; *Kesterke,* 1971; *Lindstrom and Haskin,* 1979) showed clearly that oxygen gas and iron metal are products of the electrolysis of silicate melts with compositions similar to those of the basaltic lavas that we find in the lunar maria, they did not include investigations of the nature of the electrode reactions or their kinetics. This is a difficult problem if one begins with a melt as complex as a basaltic lava, so we have done many of our fundamental studies in molten diopside ($CaMgSi_2O_6$) to which FeO has been added. To a very rough approximation, but one adequate for our purposes, the bulk composition of basaltic magmas corresponds to half diopside and half plagioclase feldspar ($CaAl_2Si_2O_8$). Our initial results for mixtures of diopside and feldspar show that the types of reactions are the same as, or very similar to, those in diopside. We conclude that our studies pertaining to diopsidic melt are applicable to basaltic melts as well.

Cathodic Reactions

There are two major metal-producing cathodic reactions; one is the following

$$\text{Cathodic: } Fe^{2+} + 2e^- = Fe^0 \qquad (1)$$

Nickel, cobalt, and zinc existing as Ni^{2+}, Co^{2+}, and Zn^{2+} in diopsidic melt each show a simple, reversible, two-electron transfer reduction (*Semkow et al.,* 1982). Our preliminary studies of iron (*Rizzo,* 1976), which is present partly as Fe^{2+} and partly as Fe^{3+}, suggest that the reduction of Fe^{2+} is also a simple reversible process, as represented by equation (1). However, these studies involved metallic-state atoms dissolved in the silicate melt. The reduction of the cations to solid or liquid metal in a separate phase would occur at potentials a few hundred millivolts more negative than observed in the studies of Semkow et al. and Rizzo. (The exact difference depends on the activities of the oxidized and reduced species in the melts.)

The second major metal-forming cathodic reaction is the reduction of Si(IV) [equation (2)]. The silicon, depending on conditions, will be alloyed to varying extents with iron.

$$\text{Cathodic: } Si(IV) + 4e^- = Si^0 \qquad (2)$$

A competing cathodic reaction is reduction of Fe^{3+} that is present in the feedstock or produced at the anode [equation (3)]. This reaction is important when the concentration of Fe^{2+} exceeds a few percent (discussed in detail below).

$$\text{Cathodic: } Fe^{3+} + e^- = Fe^{2+} \qquad (3)$$

Another competing cathodic reaction, the reduction of O_2 [equation (4)], can become important at oxygen fugacities above 10^{-4}. Since the cell produces an atmosphere of oxygen above it, and since oxygen is slightly soluble in silicate melts (Henry's Law constant ~0.023 moles/liter/atmosphere in diopside at 1450°C; *Semkow and Haskin,* 1985), some oxygen is reduced at the cathode as in equation (4).

$$\text{Cathodic: } O_2 + 4e^- = 2O^{2-} \qquad (4)$$

These reactions [equations (3) and (4)] compete with the reduction of Fe^{2+} and Si(IV) for electrons and can significantly reduce the efficiency of metal production.

Reductions of minor and trace cations such as Cr^{3+}, Cr^{2+}, Ti^{4+}, Ti^{3+}, and Mn^{2+} may also occur, but we have not yet determined the conditions for this.

Anodic Reactions

Initially, we considered the principal anodic reaction to be the following (*Lindstrom and Haskin,* 1979)

$$\text{Anodic: } 2O^{2-} = O_2 + 4e^- \qquad (5)$$

However, the reaction that produces oxygen at the anode is more complicated than equation (5) implies. Concentrations of oxide ion are buffered at very low levels in these melts, (approximately 10^{-5} mole/liter; *Semkow and Haskin,* 1985). In principle, the buffering reaction should ensure a steady supply of O^{2-}, according to the equilibrium represented by equation (6). However, the equilibrium concentration of O^{2-} is low, and the rate of depolymerization to yield O^{2-} by reaction of a pair of nonbridging oxygens is slow. Thus, reaction (5) is unimportant to practical electrolysis.

$$\text{Melt: } 2(\text{SiO-}) = (\text{Si-O-Si}) + O^{2-} \qquad (6)$$

In equation (6), (SiO-) represents a "nonbridging" oxygen attached to a silicon that is part of a polymer chain, and (Si-O-Si) represents a "bridging" oxygen attached to two Si atoms and part of a polymer chain. Bridging oxygens are presumed to form covalent bonds between two Si atoms, and nonbridging oxygens are presumed to bond covalently with one Si and more or less ionically with some other cation such as Fe^{2+} or Mg^{2+}. Independent polymer chains become linked together, or a single, long chain becomes linked to itself, when reaction (6) takes place.

The important anode reaction thus involves the breakdown of silicate anion, resulting in an increase in the extent of polymerization of the melt, as shown in equation (7). The rate of this reaction is fast.

$$\text{Anodic: } 4(\text{SiO-}) = 2(\text{Si-O-Si}) + O_2 + 4e^- \quad (7)$$

In melts with high concentrations of Fe^{2+}, the competing reaction occurs at the anode [equation (8)]

$$\text{Anodic: } Fe^{2+} = Fe^{3+} + e^- \quad (8)$$

Oxidations of Ti^{3+} and Cr^{2+} can also be expected when those species are present.

CONSTRAINTS ON CELL DESIGN

To calculate how much power is required to extract a given amount of product, we must know the resistance of the electrolytic cell and the efficiency at which O_2, Fe^0, and Si^0 are produced. These two parameters are functions of the potential imposed between the electrodes, the composition of the silicate used as feedstock, the oxygen fugacity, and the cell configuration (including surface areas of the electrodes and distance between the electrodes). By measuring melt conductivities and production efficiencies as functions of composition and potential, it becomes possible to demonstrate that a cell of reasonable and robust dimensions can be designed. Furthermore, by estimating the purity of the products and determining the effect of the product on various possible electrodes (most of which effects can be gleaned from the metallurgical literature), it is possible to put constraints on the type of materials that could survive as electrodes.

Silicate Conductivity

Resistance of the cell is a function of electrode surface area, distance between electrodes, and conductivity of the chosen feedstock. The power needed to drive the electrolysis increases as resistance increases. Thus, the limitations on the power that can be delivered, the size and weight of the electrolysis cell, and the distance the electrodes must be apart to remain robust during transport and use constrain the conductivity that the melt must have in order to conduct current adequately. Therefore, we have determined the conductivities in the temperature range 1420-1550°C of molten silicates with compositions similar to those of molten lunar rocks and soils. These determinations, like most of our other electrochemical measurements, were made on small samples (80-100 mg each) of silicate melts suspended in horizontal loops of Pt wire and held there by surface tension (see *Lindstrom and Haskin,* 1979). For conductivity measurements, a second Pt wire passed through each melt at right angles to the plane of the wire loop. The potential drop between the electrodes and across a series reference resistor provided a measurement of potential and resistance. Potentials between the electrodes of a few millivolts were used.

The values lie in the range 0.08-40 $\text{ohms}^{-1}\text{cm}^{-1}$ and are strongly dependent on melt composition, as shown in Figs. 1 and 2 (at high alternating current frequencies). These values appear adequate for robust cell design, as discussed in more detail below. Compositions of melts, made up from high-purity oxide powders, are given in Table 1. A systematic variation in conductivity with

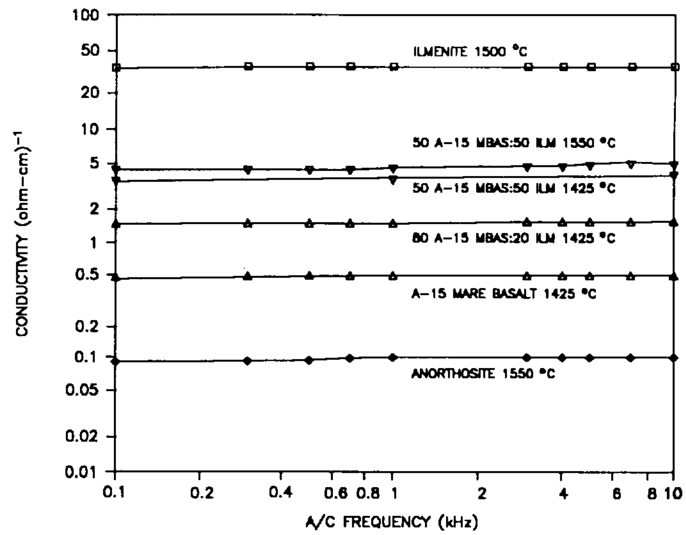


Fig. 1. Conductivities of melts of simulated Apollo 15 mare basalt, simulated anorthosite rock, ilmenite, and mixtures of simulated Apollo 15 mare basalt and ilmenite are shown as a function of alternating current frequency. Note that conductivity increases as the state of polymerization of the silicate anions (highest in anorthosite, absent in ilmenite) decreases. Note also the increase in conductivity with temperature for 50:50 mixtures of simulated mare basalt and ilmenite. Values determined in our laboratory (*Lewis,* 1985), but multiplied by 1.43 to correct for an erroneous value of the cell constant used in that work).

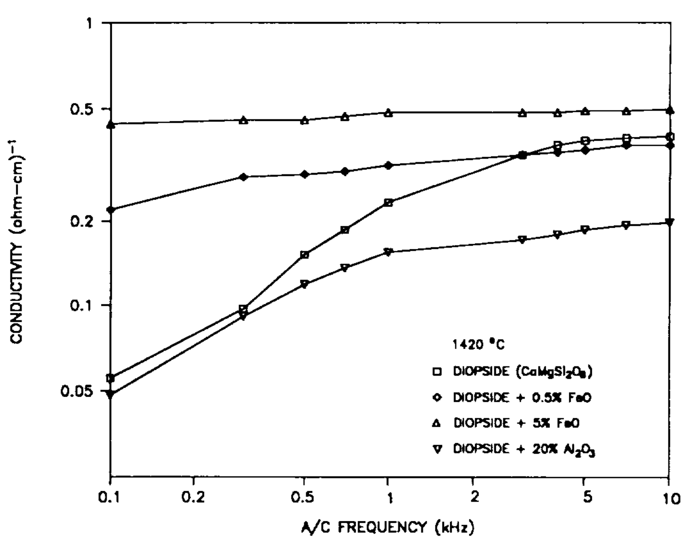


Fig. 2. Conductivities of molten diopside ($CaMgSi_2O_6$) and of diopside mixed with FeO, which increases the concentration of mobile cations and decreases the extent of silicate polymerization, and with alumina (Al_2O_3), which increases the extent of anion polymerization and lowers the conductivity. Note that the conductivities of diopside and of diopside mixed with alumina decrease with decreasing alternating current frequency, as expected for polarized melts that serve as dielectrics. In contrast, the conductivity of melts containing Fe^{2+} does not change appreciably with decreasing frequency, owing to reduction of Fe^{2+} at the cathode and oxidation of Fe^{2+} at the anode.

TABLE 1. Compositions of melts used for conductivity studies (given as oxide wt%).

	Apollo 15 Mare Basalt	Anorthosite	Ilmenite	Diopside
SiO_2	45.64	43.67		55.49
TiO_2	2.48	0.13	52.65	
Al_2O_3	9.04	33.1		
FeO	22.75	1.92	47.35	
MgO	9.9	2.69		18.61
CaO	10.18	18.41		25.9
Na_2O		0.08		

composition is observed and is shown in Fig. 3. The coefficients of the compositional parameters plotted along the abscissa were determined by linear regression.

The theoretically expected variation of conductivity with composition at constant temperature can be expressed by equation (9).

$$\text{Conductivity} \propto \Sigma X_i D_i Z^2_i \qquad (9)$$

In equation (9), X_i is the molar concentration of i, D_i the diffusivity of i, and Z_i the charge of i (*Rieger,* 1987, p. 160). This expression is similar to our empirical relationship of Fig. 3, and the values of our regression coeffficients should be related to $D_iZ^2_i$. Estimating values for D_i from the work by *Hendersen et al.* (1961) and Fig. 8 of *Henderson et al.* (1985), we have estimated values for $D_iZ^2_i$ and compare them to our regression coefficients in Fig. 4. The correlation supports the use of our empirical relationship to describe the variation of conductivity with composition.

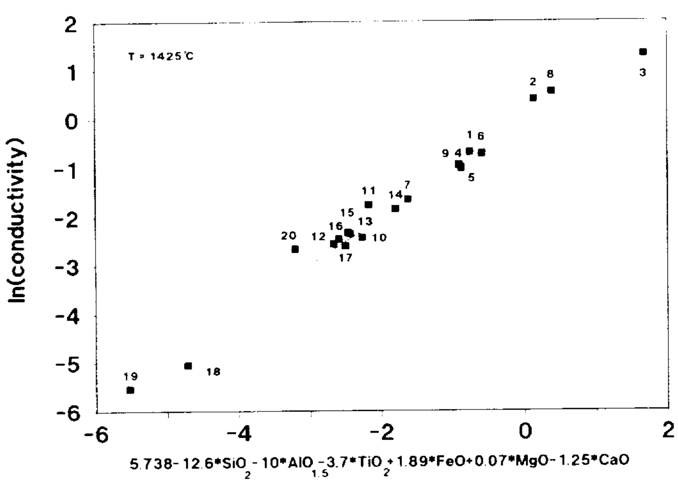


Fig. 3. Dependence of conductivity at 1425°C on melt composition. Symbols for oxides stand for mole fraction in the empirical equation used to calculate the values along the abscissa; values of the coefficients were determined by linear regression. Except where noted, data are from *Lewis* (1985). $R^2 = 0.99$. Compositions are: 1 = Apollo 15 basalt (A15); 2 = A15 + 20% Ilm; 3 = A15 + 50% Ilm; 4 = Di; 5 = Di + 0.5% FeO; 6 = Di + 5% FeO; 7 = Di + 20% Al_2O_3; 8 = Hd; 9 = Di + 0.5% NiO; 10 = Di + 50% An; 11 = A15 + 20% Ilm (FeO free); 12 = A15 (FeO free); 13 = Anorthositic gabbro; 14 = Wo + 20% Al_2O_3; 15 = Wo + 50% An; 16 = Wo + 40% Al_2O_3; 17 = Ge + 50% An; 18 = An + 20% SiO_2; 19 = An + 35% SiO_2; 20 = Anorthosite (from *du Fresne and Schroeder,* 1983).

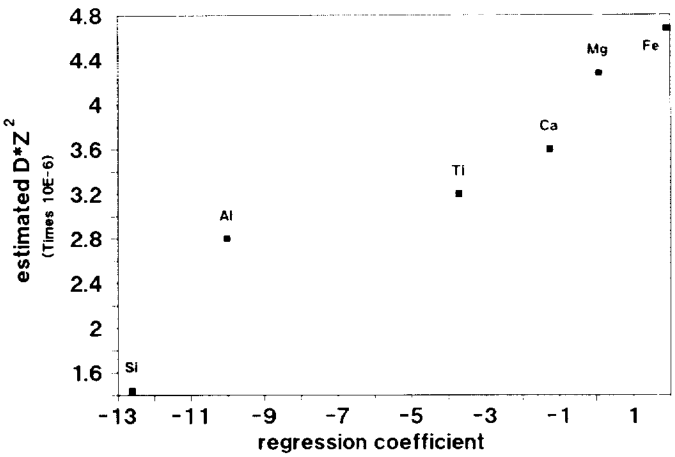


Fig. 4. Comparison between the coefficients determined by linear regression in the plot of Fig. 3 and estimates of electric mobilities (diffusivity times charge squared) of selected cations. Diffusivities for Ti^{4+}, Mg^{2+}, and Fe^{2+} were not available and are approximated roughly from Fig. 8 of *Hendersen et al.* (1985). The regression coefficients correlate well with expected electric mobilities suggesting that Fe^{2+} does not cause an unexpected increase in conductivity, such as might result from electronic conduction.

Efficiencies of Production

We consider two things pertaining to the efficiency of production of O_2 and metals. First, there was reason to suspect that significant electronic conduction might occur (semiconduction by electrons or holes). Electronic conduction in silicate melts has been previously proposed (e.g., *du Fresne and Schroeder,* 1983; *Mackenzie,* 1962; and *Simnad et al.,* 1954). The initial suggestion of this, made by *Simnad et al.* (1954), was based on an observed decrease in efficiency of oxygen production with increasing Fe concentrations in a series of melts consisting of FeO and SiO_2 in different proportions. Other evidence includes the absence of any observed change in conductivity during fusion of FeO, which is known to be semiconducting as a solid (*Mackenzie,* 1962). If there were a large component of electronic conduction, our electrolytic cell would be shorted out and efficiencies would be low.

Second, efficiencies for a given product are affected by reactions such as the reduction of Fe^{3+} to Fe^{2+} at the cathode and the oxidation of Fe^{2+} at the anode, which in turn depend on the composition of the melt. The composition of the melt also affects the composition of the metal produced through the proportions of Si(IV) and Fe^{2+} reduced at the cathode.

Electronic conductivity in iron-bearing silicates? The near constancy of conductivity with alternating current frequency seen in Fig. 1 does not at first appear to be consistent with current flow by simple ionic conductivity in the melt. If a direct potential is emplaced across two electrodes in an ionic melt, ions of positive charge migrate toward the cathode and those with negative charge away from it, and vice versa for the anode. This process continues only momentarily, until the electric field produced by the external potential is matched by an equal potential of opposite polarity resulting from partial separation of charges in the melt, a condition known as "polarization" of the melt. When this occurs, no more net separation of charge can

occur in the melt, and the current falls to zero. Thus, the melt serves as a dielectric and the device behaves as a capacitor, unless potentials are high enough to reduce or oxidize ions in the melt, in which case the discharge of ions at the two electrodes offsets the polarization.

At high alternating current frequencies, there is insufficient time for ions to migrate far enough in one direction to polarize the melt. Thus, potential differences between electrodes induce migration of ions within the melt, resulting in flow of current. As the frequency of the alternating current is decreased, partial polarization takes place, decreasing the average strength of the electric field over each cycle, and thus decreasing the mean value of the current per cycle. Finally, at the lowest of frequencies (direct current), the melt polarizes completely and there is no current beyond the initial polarizing current.

The expected decrease of conductivity with decreasing alternating current frequency is readily seen for molten diopside, $CaMgSi_2O_6$, and for molten mixtures of diopside and alumina (Fig. 2). Addition of even a small amount of FeO to the melt drastically increases the conductivity of diopside at low alternating current frequencies. This effect has been interpreted by some investigators as suggesting electronic conductivity in transition metal-bearing silicates. The same effect is seen when CoO or NiO are added to the melts.

Efficient electrolysis requires that passage of current between melt and electrode be by discharge of ions at the electrode, not by direct transfer of mobile electrons and holes that can move through the melt. Thus, we have done experiments to determine whether an appreciable fraction of the conductivity in iron-bearing silicate melts is by strictly electronic means. The evidence suggests that there is no appreciable electronic conductivity. The reasons are as follows:

1. The increase in conductivity per mole of divalent ion added is nearly the same for the transitional elements Fe^{2+}, Co^{2+}, Ni^{2+}, and Zn^{2+} as for the nontransitional elements Mg^{2+} and Ca^{2+}. It corresponds closely to the increase expected per mole from increasing the concentrations of mobile divalent cations relative to sluggish, highly polymerized silicate anions. The relative effects of different cations on conductivity can be seen from Figs. 3 and 4. The increase in conductivity from adding Fe^{2+} is close to that expected based on Fe^{2+} diffusivity, suggesting that the melt structure does not change in a fundamental way to enable a new form of conductivity when the transitional elements are added.

2. The conductivities of diopside and diopside plus alumina (Fig. 2) are low compared with that of diopside plus small concentrations of added FeO. If the difference reflects electronic conduction by iron-bearing melts, the bulk of the conduction in those melts should be electronic. However, preliminary measurement of the efficiency of electrolysis for reduction of Fe^{2+} to Fe^0 in our test system ($\geq$60%; *Lindstrom et al.*, 1986) shows that the bulk of the conductivity must be ionic. In these small samples, we expect that at least some Fe^{3+} and O_2 find their way to the cathode through convection, requiring that some additional oxidation and reduction take place. This leaves little, if any, current to be accounted for by electronic transport.

3. Addition of the transition metal ion Zn^{2+} raises the conductivity at high frequencies to an extent commensurate on a per mole basis to that of the other divalent ions, but does not maintain the level of conductivity at low frequencies that Fe^{2+}, Co^{2+}, and Ni^{2+} do. Thus, an ion that can be reduced almost as easily as Fe^{2+}, Co^{2+}, and Ni^{2+} does not show the effect.

This suggests that the ability of Fe^{2+}, Co^{2+}, and Ni^{2+} to be reduced to the metallic state or oxidized to the 3+ state accounts for the relatively high conductivities at low alternating current frequencies. The tendency for Fe^{2+} to oxidize to Fe^{3+} competes with oxygen production, and this presumably explains the observations of *Simnad et al.* (1954). In systems containing those ions, whatever polarity the electrodes have, ions can be discharged at both electrodes. This cannot occur when only Mg^{2+} or Ca^{2+} is present, because their reduction potentials exceed the breakdown potential for polymeric silicate and their oxidation potentials would be extremely high. It cannot occur when Zn^{2+} is added because, although Zn^{2+} reduces readily at the cathode, its oxidation potential is so high that no complementary anodic reaction can occur.

Given this mechanism for maintenance of the high conductivity, we can describe the resistance of our electrolytic cell, at least approximately, in terms of the circuit diagram shown in Fig. 5. The resistance R_i represents the resistance of the melt to ionic conduction (related to the intrinsic mobilities of the ions in the melt); R_c represents the resistance associated with reduction at the cathode and is related to the reduction potentials of Fe^{2+} and Si(IV) and their concentrations in the melt; R_a represents the resistance associated with oxidation at the anode and is related to the oxidation potential of the silicate anions; C represents the electrode-melt capacitance.

Competing reactions at the cathode. As discussed above, several competing reactions can occur at the cathode along with the reduction of Fe^{2+}. We have estimated the dependence of the efficiency of Fe metal production on potential and on electrolyte composition by a combination of theoretical treatment and experiment. Experiments were designed to determine the difference between "background" current flow (related to reductions other than Fe^{2+}) and total current. This was done by measuring current as a function of potential (in this case, cathodic potential relative to the potential of the bulk electrolyte) for both a silicate melt containing Fe^{2+} and a silicate melt in which a molar-equivalent amount of electroinactive Mg^{2+} had been substituted for Fe^{2+}.

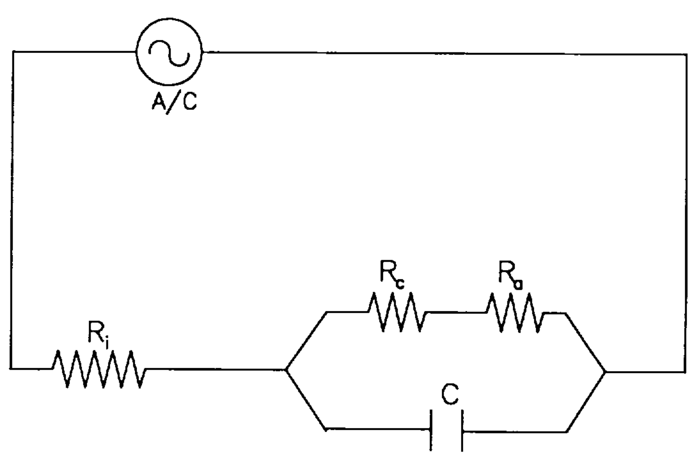


Fig. 5. Circuit diagram model to represent the electrical properties of the molten silicates. The overall resistance of the cell to alternating current stems from the combined resistance of ionic conductivity (R_i), the threshold potentials for the cathodic and anodic redox reactions (R_c and R_a), and the charging current capacitance of the cell as it polarizes (C).

Figure 6 shows cathodic current as a function of electrode potential for several compositions. The "background" current is for a composition in which Mg^{2+} has been substituted for Fe^{2+}. This current is related primarily to the reduction of Si(IV). If we assume that no current is lost to electronic conduction (as discussed above), then the figure gives a rough estimate of the relative amounts of the total current that can be attributed to the Fe^{2+} and Si(IV) reductions at various potentials and Fe^{2+} concentrations. However, for these compositions and potentials, much of the reduced Fe^0 is dissolved in the melt or in the Pt electrodes and does not exist as precipitated, pure metallic Fe.

Threshold potentials for the precipitation of pure metallic Fe were calculated from the data presented by *Grove* (1981) and are plotted as a function of cation mole percent of Fe^{2+} in Fig. 7. Figure 7 indicates that, in the range of potentials 0 to -250 mV, pure metallic Fe can only be precipitated at concentrations >11 mol% Fe^{2+} (or FeO). Comparison with Fig. 6 indicates that at those potentials and concentrations, the amount of Fe^{2+} reduced will be very large compared to the amount of Si(IV) reduced.

We conclude that at high Fe^{2+} concentrations (>20% FeO) and low potentials (e.g., 0 to -0.4 V at $fO_2 = 10^{-8}$), the cathode product is primarily Fe^0. At lower Fe^{2+} concentrations (<5% FeO) and higher potentials (e.g., >0.4 V at $fO_2 = 10^{-8}$), the cathodic product is primarily Si^0.

Competing reactions at the anode. Efficiency of O_2 production [defined as moles of O_2 produced/(moles of electrons passed through the melt/4)] is calculated from the amount of O_2 produced and the measured total current flow in an electrolysis experiment. The amount of O_2 produced is determined from the difference in sample weight before and after the experiment.

We find that the primary reaction competing with oxygen formation at the anode is the oxidation of Fe^{2+}. This oxidation controls the dependence of oxygen production efficiency on electrode potential, oxygen fugacity, and electrolyte composition. Oxygen production efficiency decreases as Fe^{2+} concentration increases. Fe^{2+} concentration increases both as the melt becomes richer in iron and as oxygen fugacity decreases. If we assume that all the current is related to oxidation of either oxygen ions or Fe^{2+}, we can estimate the relative proportions of the current attributable to each oxidation by equation (10), where $\%Fe^{2+}$ is the percent of the current attributed to the oxidation of Fe^{2+}, $\%O_2$ is the percent of the current producing oxygen, $X(Fe^{2+})$ is the cation mole fraction of Fe^{2+}, and $X(O^{2-})$ is the mole fraction of oxidizable oxygen (which we assume is constant).

$$\%Fe^{2+}/\%O_2 = X(Fe^{2+})/X(O^{2-}) \tag{10}$$

If we further normalize the concentrations of these electoractive species such that $\%Fe^{2+} + \%O_2 = 100\%$, equation (10) can be modified to yield equation (11).

$$\%O_2/(100\text{-}\%O_2) = X(O^{2-})/X(Fe^{2+}) \tag{11}$$

This relationship adequately describes the observed dependence of O_2 efficiency on composition and oxygen fugacity, as is shown in Fig. 8. The dependence of $\%O_2$ on total Fe (rather than ferrous Fe) [equation (13)] can be obtained from the expression for equilibrium [equations (12) and (11)].

$$X_{FeO} = X_{FeO1.5}/(fO_2^{1/4}e^{-\Delta G/RT}) \tag{12}$$

In equation (12), ΔG is the Gibbs Free Energy for the oxidation of FeO to $FeO_{1.5}$. X_{FeO} (or Fe^{2+}; we express the concentrations for all cations as cation mole fractions) can be expressed as $X_{totalFe}/fO_2^{1/4}e^{-\Delta G/RT} + 1)$ and substituted into equation (11) to give equation (13).

$$\%O_2/(100\text{-}\%O_2) = XO^{2-}(fO_2e^{\Delta G/RT} + 1)/X_{totalFe} \tag{13}$$

ΔG is a function of composition and temperature, and estimates of its value can be made from studies such as that of *Sack et al.* (1980).

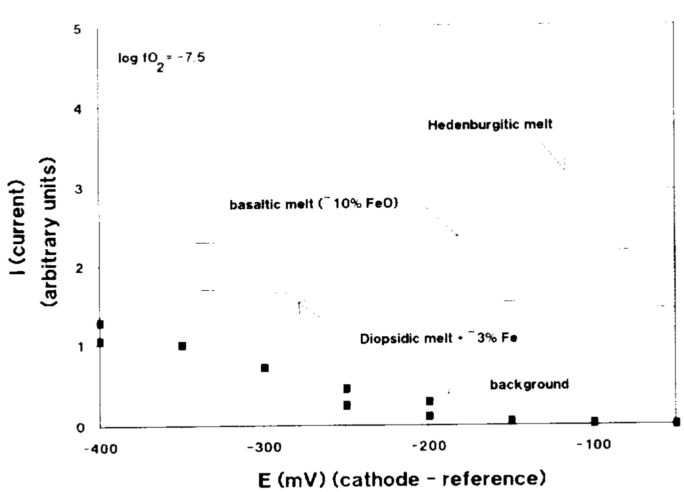


Fig. 6. Proportions of current (as a function of cathode potential) that can be attributed to Si(IV) reduction (background) and Fe^{2+} reduction (other curves minus background) for melts of several Fe^{2+} concentrations. Note that the proportion from Fe^{2+} reduction increases as Fe^{2+} concentration increases and decreases with increasing potential.

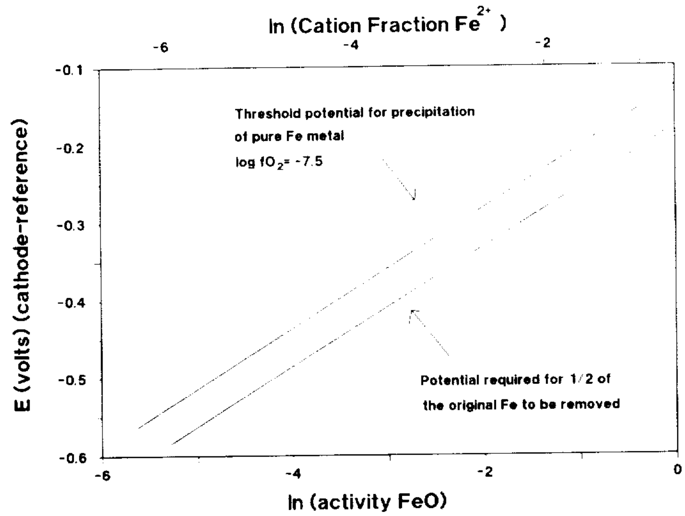


Fig. 7. Potential required to reduce Fe^{2+} to Fe^0 in the presence of pure metallic Fe, estimated from the data of *Grove* (1981). Activity of FeO is defined in *Grove* (1981), $AFeO = XFe^{2+}/(XFe^{2+} + XMg^{2+} + XCa^{2+} + XAl^{3+} - XK^+ - XNa^+)$ where X denotes cation mole fraction. An approximate conversion to a standard state of activity of Fe^{2+} defined as a simple cation fraction is shown along the top of the figure. Note that these potentials are somewhat more negative than the lowest potentials in Fig. 6, in which significant current flow is observed, reflecting the dissolution of the Fe^0 of the experiments of Fig. 6 in the melt and in the Pt electrodes.

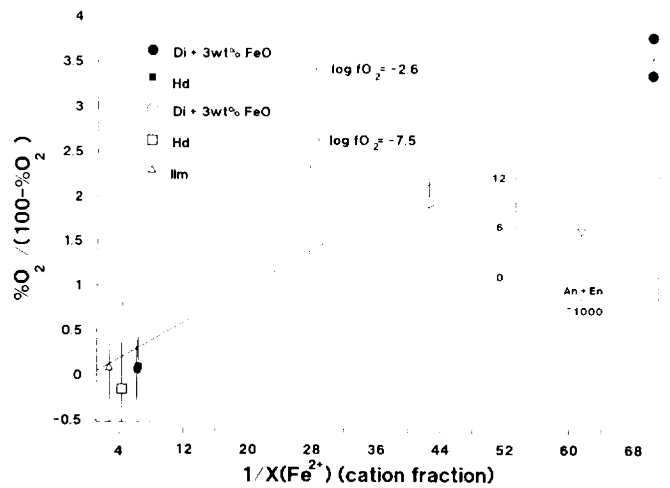


Fig. 8. Dependence of O_2 production efficiency on Fe^{2+} concentration in the melt. The mole fraction of Fe^{2+} as a function of fO_2 is calculated from the concentration of total iron and the reduction potential for Fe^{3+}.

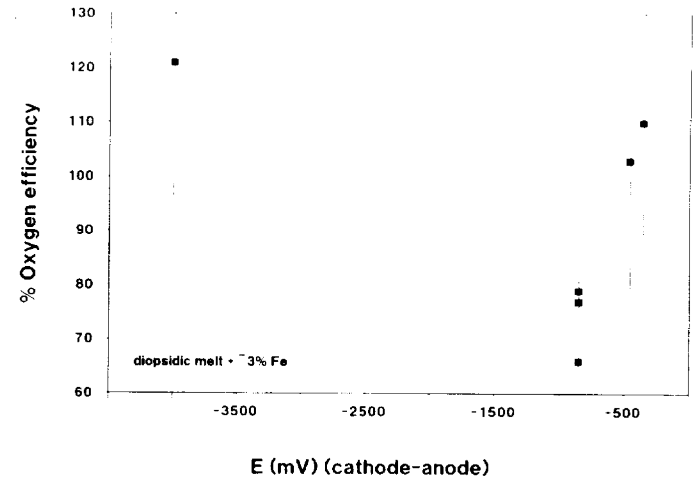


Fig. 9. Dependence of O_2 production efficiency on potential. The lowest efficiences are near the Fe^{3+} reduction potential. Bars show estimates of uncertainty.

The dependence of O_2 efficiency on cell potential (Fig. 9) can also be related to the oxidation of Fe^{2+}. The low point in the oxygen efficiency curve is near the reduction potential for Fe^{3+}. (Based on Fe^{3+} reduction potentials, we estimate about 35-65% of the Fe^{2+} is oxidized at these potentials.) At potentials less negative than the reduction potential for Fe^{3+}, only a small fraction of the Fe^{2+} is oxidized to Fe^{3+} (we estimate 5-10%). At higher potentials the amount of Fe^{2+} that is oxidized is small compared to the amount of oxygen because oxygen is so much more abundant in the melt than Fe^{2+}. However, for melts with high Fe^{2+} concentrations, increasing the potential does not significantly increase the efficiency of O_2 production. We conclude that high efficiencies for O_2 production require low Fe^{2+} concentrations, high oxygen fugacity (from the point of view of high Fe^{3+}/Fe^{2+}, but not from the point of view of the competing cathode reduction of O_2), and high potentials. These conditions are the opposite of those required for high Fe^0 production efficiencies.

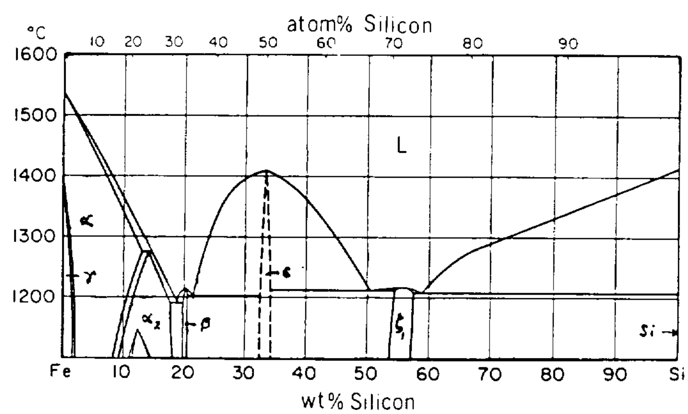


Fig. 10. Silicon-iron binary phase diagram, adapted from *Hultgren et al.* (1973).

Electrode Materials

Several considerations must be made in choosing a material for the cathode. First, the cathode must be inert to or in equilibrium with the cathodic product. The cathode must either be solid itself or it must be contained within a solid that is inert to or in equilibrium with the cathode material, the cathode product, and the silicate melt. Because a solid product may short out the cell by forming dendrites that bridge between electrodes, it is also desirable that the cathode material have a melting point higher than that of the cathodic product. Because the cathodic product will be mostly Fe^0 and Si^0 (minor amounts of Mn^0, Ti^0, and Cr^0 being ignored here), the Si-Fe phase diagram (Fig. 10) is one key to the composition of the cathode.

Basically, three types of Si or Si-Fe electrodes can be used, each one stable relative to different compositions of Si^0-Fe^0 melt. These are pure Si^0 (stable relative to a molten Si-Fe alloy between 0 and about 40 wt% Fe), Fe(67 wt%)-Si alloy (stable relative to a molten Si-Fe alloy between about 50 and 78 wt% Fe), and solid solutions between about 87% and 100% Fe^0 (stable relative to a melt that is only slightly more Si^0-rich than the solid electrode). For an electrolysis aimed at high oxygen production efficiency (therefore having low Fe^{2+} concentrations in the electrolyte with a high Si/Fe ratio in the cathodic product), a Si^0 electrode may be the one of choice despite the high resistivity of Si^0. For electrolysis aimed at Fe^0 production, the Fe-rich alloy electrode may be the one of choice. At high temperatures (e.g., >1200°C), the specific conductivities of these proposed electrode materials are high enough to serve in a practical cell (Fe: *Weast,* 1982; Si: *Pearson and Bardeen,* 1949).

An alternative approach may be applicable if nearly pure Fe^0 is precipitated at the cathode. It is an Fe^0 cathode that also serves as the container and is dynamically cooled such that its outer portions are solid and its inner portions are molten.

A third approach is adapted from one formerly used in the commercial production of Fe-Si alloys. In that process, heat was provided by electrodes positioned near the middle of an electric furnace. The iron silicate feedstock melted in the middle of the furnace but remained chilled against the container walls. The chilled margin served as insulation protecting the container from the reactive silicate melt and the Fe-Si alloy product (*Greiner,* 1933, p. 17).

For the anode, we suggest Pt, possibly in the form of a screen to aid the escape of oxygen bubbles. Silicate melts are extremely corrosive, and few materials can retain their integrity when subjected to them. In preliminary studies (*Semkow and Haskin,* 1986) we investigated the oxidization of Pt as a function of electrode potential and time. In an air atmosphere at 1300° to 1500°C, formation of oxides was the most rapid when the potential of the Pt anode was about 0.2 V positive relative to a separate Pt reference electrode in the same melt. The electrodic oxidation was complex and only a portion of it appeared to be reversible. Nevertheless, during a 5-hr electrolysis of 10 g of molten, iron-rich basalt simulant at a current density of 2.5 A/cm^2 at 1560°C, during which vigorous production of oxygen bubbles was observed, little if any Pt was lost from the anode, a Pt wire of 0.083-cm diameter. Furthermore, efficiencies of as much as 85% for production of O_2 indicate that little of the oxygen reacts with the Pt of the electrode. We surmise that the interior of the electrode may be protected by an outer layer of oxide, and that the rate of evolution of oxygen gas may be in a steady state equilibrium set by the rates of formation and thermal decomposition of oxide in the layer.

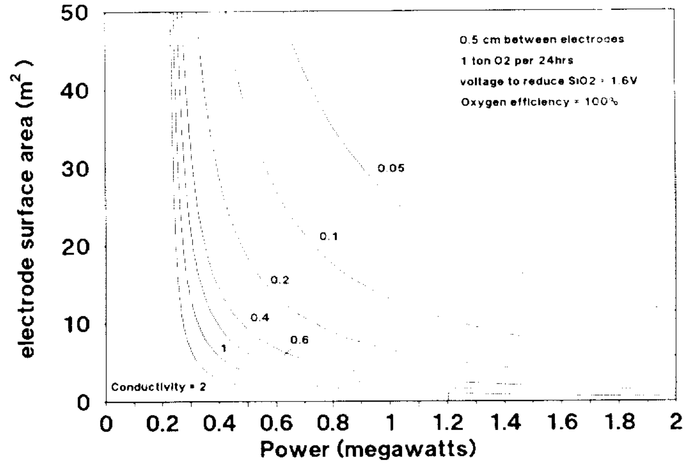


Fig. 11. Effect of electrode surface area and melt conductivity (in ohm^{-1}cm^{-1}) on power required to produce 1 tonne O_2 per 24 hr when the oxygen production efficiency is 100% and the distance between electrodes is 0.5 cm. The potential required to overcome kinetic problems and reduce SiO_2 is taken to be 1.6 V. The energy (in MWhr) to produce 1 tonne of O_2 can be derived from the figure by multiplying the power by 24.

EXAMPLE CELL PARAMETERS

Our purpose in this section is to demonstrate that, given our measured conductivities and production efficiencies, an electrolytic cell of reasonable dimensions and production volume can be designed. The variables whose values determine the necessary size and power requirements for the cell include the current necessary to provide oxygen at the desired rate (which must take into account the efficiencies of production), the required energy for the reduction and oxidation processes (including the energy to reduce the oxides and any overpotential required to overcome kinetic problems), and the energy lost to resistance heating of the melt (related to the electrode surface area, the distance between the electrodes, and the melt conductivity).

Some of these variables are constrained by the demands of reasonable cell construction. We select an electrode separation distance >0.5 cm to make sure that the cell will be physically robust. Somewhat arbitrarily, we have constrained the anode and cathode surface areas each to be less than 30 m^2. Some 200 m^2 of electrode surface area can be fit into 1 m^3 volume if 1 m^2, two-sided electrodes are each 1 cm apart. The power should be kept as low as feasible to keep costs low and must not cause runaway heating of the melt. We also choose a production rate for O_2 of 1 tonne per 24 hr. With these constraints in mind, the effect of conductivity and O_2 production efficiency on power requirements are seen in Figs. 11 and 12.

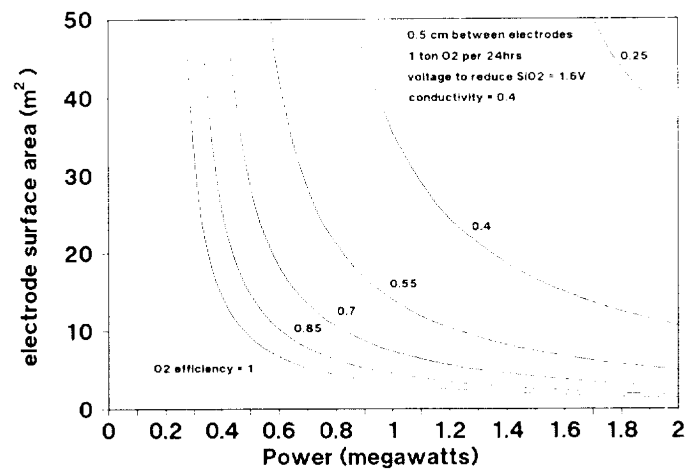


Fig. 12. Effect of electrode surface area and oxygen production efficiency on power required to produce 1 tonne O_2 per 24 hr when the conductivity is 0.4 ohm^{-1}cm^{-2} and the distance between electrodes is 0.5 cm.

In these figures, the potential required to reduce Fe^{2+} and Si(IV) is taken to be 1.6 V. This potential is considerably greater than that necessary to reduce Fe^{2+} and is sufficient to reduce Si(IV). For conductivities above about 0.4 ohm^{-1}cm^{-1}, efficiencies >0.85 (or 85%), and electrode surface areas >20 m^2, the power required quickly approaches the theoretical minimum value of 0.224 MW. These are encouraging results but, as demonstrated above, efficiency of oxygen production is favored by low Fe^{2+} concentrations in the melts. The effect of this is seen in Fig. 13, which illustrates power requirements for several different compositions with different O_2 efficiencies and conductivities.

As seen from the figure, the power requirement to electrolyze the high-Fe compositions is high, in the range 24-48 MWhr/tonne O_2. This limits us to using either a relatively specialized lunar material such as dunite, which has high concentrations of Mg^{2+} and thus good conductivity and which also has a low concentration of Fe^{2+}, or using a more common material such as magnesian norite or anorthositic norite, which have lower conductivities. Dunite is not known to be as readily available (e.g., in soil form) as materials of more noritic or basaltic compositions, and its high liquidus temperatures make it harder to work with (its liquidus temperatures exceed the melting temperatures of the proposed Si electrodes and container). However, as will be shown below, basaltic and noritic materials work well because their concentrations of Fe^{2+} and Si(IV) are lowered during the progress of electrolysis, increasing the efficiency and conductivity of the melt.

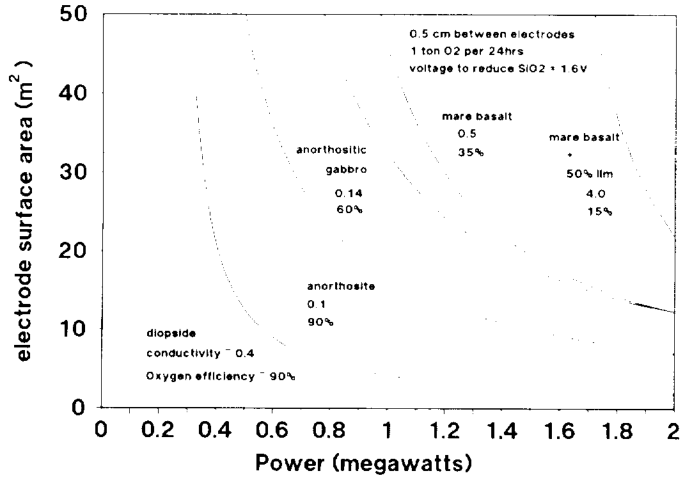


Fig. 13. Power required to produce O_2 at the rate of 1 tonne/24 hr for the conductivities and production efficiencies determined for several real compositions. Power requirements for the high-Fe compositions are high because of the low production efficiencies.

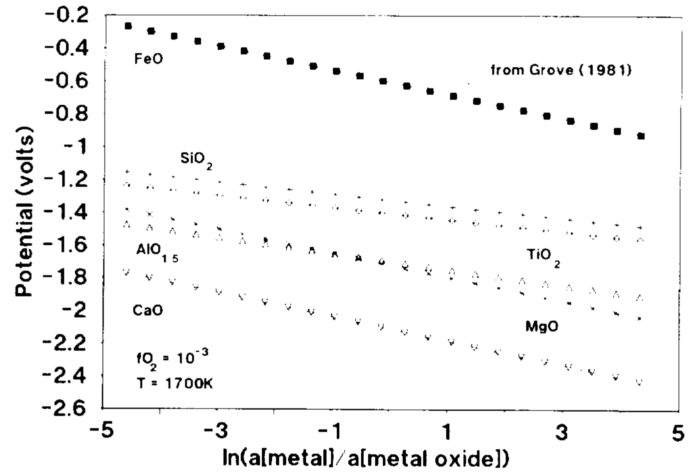


Fig. 14. Relationship between applied potential and equilibrium activities in metal and silicate melt for several oxides at $fO_2 = 10^{-3}$ and temperature = 1700 K. Data are from *Robie and Waldbaum* (1968). The line from *Grove* (1981) is from actual measurements in basaltic melts translated to a standard state in which activity of FeO in the melt is defined as cation mole fraction Fe^{2+} to correspond to the standard state of this study.

Given the data presented in this paper and the thermodynamic data of *Robie and Walkbaum* (1968), presented in Fig. 14, it is possible to follow theoretically the progress of the electrolysis of a single batch of basalt and calculate the power required to produce 1 tonne of O_2. In these calculations we assume ideal solution in the melt and in the metal produced, which introduces some error into the results. However, our own observations of silicate breakdown potential and those of *Grove* (1981) for FeO (e.g., see Fig. 14) demonstrate that for the reduction of Fe^{2+} and Si(IV) any resultant error in the estimates of power consumed will be <20%. The reductions of other species [(Al^{3+}, Mg^{2+}, Ca^{2+}, Ti(IV)] are given for demonstration and may not be numerically exact although they are approximately correct.

In this theoretical electrolysis, we incrementally reduce 0.57 kg of a six-component (SiO_2 = 46.2 wt%, Al_2O_3 = 12.6%, TiO_2 = 2.8%, FeO = 17.4%, MgO = 10.4%, CaO = 10.6%) basaltic melt of a composition similar to Apollo 12 soil (12001; *Laul and Papike*, 1980). At each increment, we recompute the conductivity of the melt (from the relationship in Fig. 3), the production efficiency (from Fig. 8, ignoring contributions from the oxidation of Ti^{3+}), and the equilibrium distribution of components between silicate melt and metal [from the thermodynamic data of *Robie and Waldbaum* (1968) and mass balance constraints, using Newton's method of approximation to solve numerically for the system of 12 nonlinear equations]. The computed variations in conductivity, production efficiency, and remaining amounts of oxides in the silicate melt are shown in Figs. 15 and 16. Although the computations were carried to the point that only CaO remained in the liquid, precipitation of spinel would begin under the conditions of the hypothetical electrolysis (T = 1425°C) at about 35-40 moles oxygen produced.

The potential applied across our imaginary electrolysis cell is

$$E_{applied} = E_C - E_A - \eta_C - \eta_A - i \cdot (R_{cell}) \qquad (14)$$

Here, $E_C - E_A$ is the potential required to reduce the oxides (from which the equilibrium oxide/metal values are calculated), $-\eta_C - \eta_A$ is the overpotential required to drive the reaction at a

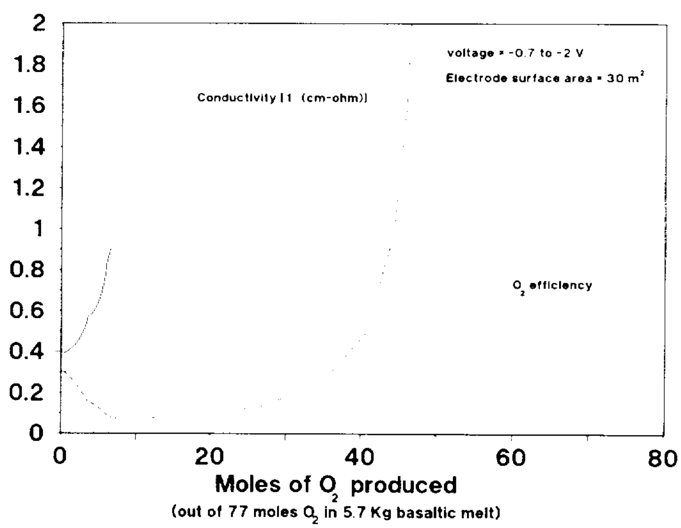


Fig. 15. Moles of O_2 produced as an index of the progress of electrolysis at 1425°C are plotted against conductivity and O_2 production efficiency in accordance with the thought experiment described in the text. This illustrates how these parameters would vary if no interfering process occurred; in fact, at this temperature, spinel is expected to precipitate when 35-40 moles of oxygen have been produced.

sufficiently high rate (which we assume is 10% of $E_C - E_A$), i is the current, and R_{cell} is the cell resistance; $R_{cell} = L/(\kappa \cdot A)$, where L is the distance between electrodes, A is the surface area of each electrode, and κ is the melt conductivity. For this exercise, we have chosen L = 0.5 cm and A = 10 m^2 or 30 m^2. The value of $E_C - E_A$ was either increased incrementally from -0.7 to -2 V or was held constant at -1.5 V. The value of pO_2 was held constant at 10^{-3} atm and temperature was 1425°C. The current depends on the constraint that at all times we produce oxygen at the rate

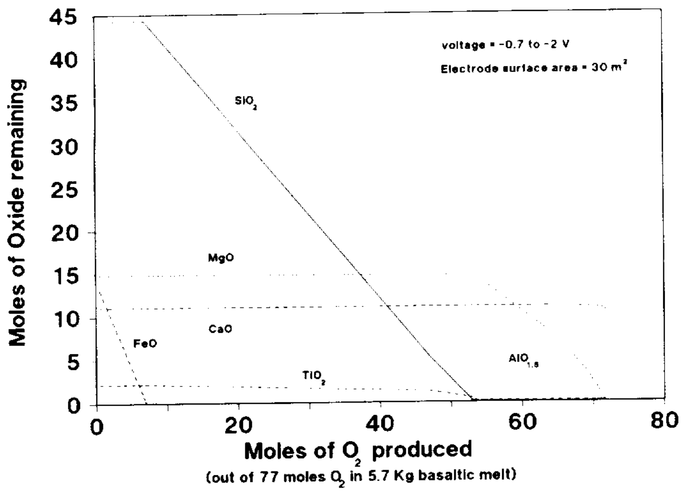


Fig. 16. Moles of oxides remaining (out of 5.7 kg original melt) in the silicate melt during the progress of electrolysis. Same conditions and limitation as in Fig. 15.

of 1 tonne/24 hr (about 140,000 amperes) and on the efficiency of oxygen production, or i (in amperes) = 140,000/O_2 efficiency. The variations of potentials and current during the progress of electrolysis for the case of A = 30 m^2 with E_C - E_A increasing from -0.7 to -2 V are shown in Fig. 17.

Energy requirements per tonne of O_2 as a function of extent of electrolysis are shown in Fig. 18. Energy values for three cases are shown, A = 10 m^2 with potential increasing from -0.7 to -2 V, A = 30 m^2 with potential increasing from -0.7 to -2 V, and A = 30 m^2 with potential constant at -1.5 V. For reduction of one-half of the Si(IV) originally in Apollo 12 soil with an electrode of surface area of 30 m^2 and distance between electrodes = 0.5 cm, the energy required per tonne of O_2 is about 13 MWhr, for an average power requirement of 0.54 MW. Both the conductivity and the production efficiency of the melt improve during the progress of electrolysis; therefore, the extent to which a melt can be electrolyzed depends only on whether the melting point of the residual melt gets too high and, ultimately, on the electrochemical properties of Al^{3+}, Ca^{2+}, and Mg^{2+}, which we have not yet studied. However, based on the phase diagrams of *Osborn et al.* (1954), about half the Si(IV) can be reduced before the liquidus temperature rises above 1425°C and spinel becomes insoluble. If half the original Si(IV) and Ti(IV) is reduced, the amount of Fe^0 produced per 13 MWhr and per 24 hr and per tonne O_2 is about 0.81 tonne, the amount of Si^0 is about 0.65 tonne, the amount of Ti^0 is 0.05 tonne, and the amount of residual silicate melt (with a composition of roughly 40 wt% SiO_2, 2% TiO_2, 22% Al_2O_3, 18% MgO, and 18% CaO) is about 3.5 tonnes.

The feedstock input rate required to derive 1 tonne of O_2 per day under the conditions of the exercise above is about 69 g of feedstock per sec (6.0 tonnes/day). At a density of about 1.5 g/cm^3 for feedstock, this corresponds to some 47 cm^3 of feedstock per sec.

We estimate the energy to convert lunar soil to melt at 1250°-1500°C to be about 480 cal/g, which, at 69 g/sec, corresponds to 0.14 MW. Considering that the reduction requires an additional 0.19 MW, the 0.54 MW (Fig. 18) to operate the cell adds excess resistance heat to the cell at a rate of 0.21 MW. This "waste heat" must be removed from the system.

Actual cell design would take into account that more favorable cell parameters (e.g., larger electrode area or shorter distance between electrodes) or more favorable feedstock conductivity would reduce both the power required and the amount of waste heat. It may be possible to select conditions under which a favorable steady-state composition can be attained for the material in the cell. This composition would lie in the favorable range of conductivity, one corresponding to a substantial reduction in Si(IV) concentration. Such a composition could substantially reduce the excess resistance heating and the corresponding excess power needed.

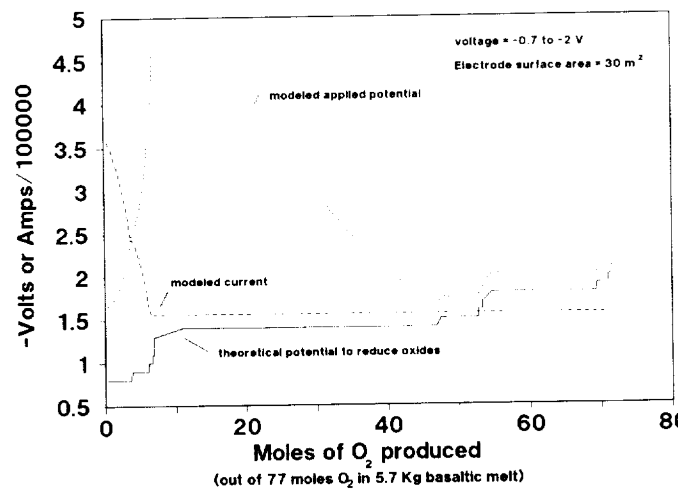


Fig. 17. Variation of imposed potential and current during progress of electrolysis in the thought experiment discussed in the text. By multiplying the maximum voltage by current it is seen that the maximum power requirement is about 0.76 MW. Same conditions and limitation as in Fig. 15.

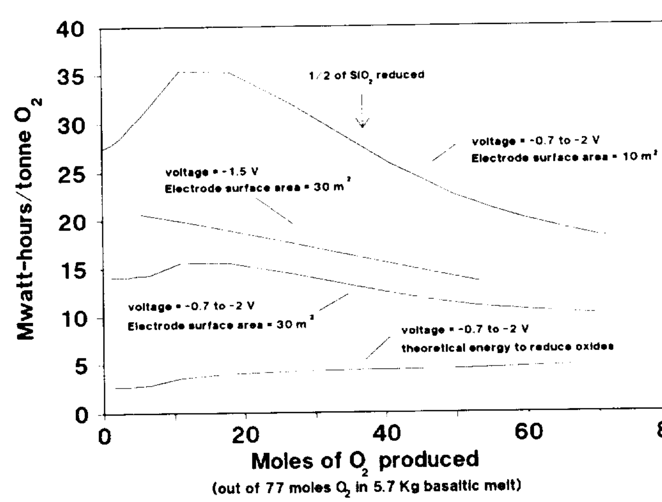


Fig. 18. Energy requirement to produce 1 tonne of O_2 from a basaltic melt of the composition of Apollo 12 soil for the three cases discussed in the text and for the case where no energy is lost to resistance heating, kinetic problems, or low production efficiencies. Same conditions and limitation as in Fig. 15.

In any event, the power going into "waste heat" need not be wasted. Some will be needed to make up for radiation losses from the cell. Depending on conductivities and how the cell is configured, the rest may be regarded as a by-product that can be put to use. For example, both the "waste heat" and the heat contained in the metal and silicate products could be used to heat lunar soil to extract valuable solar-wind implanted gases (H, C, N, and noble gases), or to provide light and heat during the long lunar night. Both the Fe-Si alloy and the residual silicate have to be molten to convert them to useful products. Producing them in the electrochemical cell merely requires that, for efficient use of energy, the appropriate casting forms or drawing or spinning devices handle these materials as they leave the cell.

We have not considered in detail the problems of containers and operations in a cell at high temperature, how to remove and handle the products, or the actual design of an efficient and robust cell. We envision a continuous feed of lunar soil to the cell, and melting of the feedstock by a combination of solar heating and resistance heating. It would seem desirable to have the capability to furnish the entire power for the cell by a source that would not be disrupted by the long lunar nights. The distance between the electrodes could be adjusted during the lunar day to reduce the electrical heating and take advantage of presumably cheaper solar heating (even, perhaps, power) during the lunar days, with the main power coming from a source such as a nuclear reactor, whose share would be increased during the lunar nights.

The apparatus must be housed in a gas-tight container that will capture the oxygen liberated and allow it to be pumped to storage or shipping containers. The dimensions of the housing must be large enough and the materials of the housing refractory enough to be stable in the high-temperature and oxygenating conditions of the cell.

The Si-Fe product can be purified by other techniques to yield Si^0 and Fe^0 or it can be used as ferrosilicon to take advantage of the properties of high-Si iron. These include lower density, corrosion resistance, higher resistivity, lower thermal conductivity, either greater or lesser strength (depending on Si concentration), increased hardness, and reduced ductility. Ferrosilicon can also be used in the manufacture of silicon steels.

Pure Si^0 derived at the cathodes or extracted from the purification of Fe-Si melt can be used in semiconductors (low-volatile conditions on the Moon may make purification of Si easier than it is on Earth), for surfacing mirrors (Si is currently used on Earth for surfacing of dental mirrors), and in photocells. Reoxidation of Si could yield high-purity SiO_2, which could be a source of transparent glass. The residual silicate melt can be used to make beams, rods, tubes, plates, and fibers, which will surely be important if not the dominant constructional materials for use in space. These may have unusually good properties in the water-free space environment, where water will not react with stressed bridging oxygen bonds (e.g., *Blacic,* 1985).

Iron produced by purification of Fe-Si alloys, or by electrolytic precipitation of pure Fe^0 may be used not only as constructional material but for applications we would not consider seriously on Earth, e.g., to surface mirrors (iron will not rust in low lunar pO_2), or as electrical conductors. Copper is very rare on the Moon, and Al is more difficult than Fe to wrest from lunar rock or soil.

The estimates given above demonstrate that the electrochemical properties of lunar silicate melts of themselves do not preclude a practical cell design. Because of the simplicity of the concept and because the power required in this estimate is only about twice the theoretical minimum for separating oxygen from silicate, we anticipate that the process may be quite competitive with others that may be proposed for extracting oxygen from lunar soil or other water-free extraterrestrial silicate materials.

Acknowledgments. We thank C. R. Keedy for his careful review of the manuscript. We appreciate the partial support of this work by the National Science Foundation under grant DAR 79-24705 and by the National Aeronautics and Space Administration under grant NAG 9-56 and through the UA/NASA Space Engineering Center for the Utilization of Local Planetary Resources.

REFERENCES

Arnold J. R. (1979) Ice in the lunar polar regions. *J. Geophys. Res., 84,* 5659-5668.

Blacic J. D. (1985) Mechanical properties of lunar materials under anhydrous, hard vacuum conditions: Applications of lunar glass structural components. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 487-495. Lunar and Planetary Institute, Houston.

du Fresne E. and Schroeder J. E. (1983) Magma electrolysis. In *Research on the Use of Space Resources* (W. F. Carrol, ed.). JPL Publication 83-36.

Greiner E. S., Marsh J. S., and Stoughton B. (1933) *The Alloys of Iron and Silicon.* McGraw-Hill, New York.

Grove T. L. (1981) Use of FePt alloys to eliminate the iron loss problem in 1 atmosphere gas mixing experiments: Theoretical and practical considerations. *Contrib. Mineral. Petrol., 78,* 298-304.

Haskin L. (1992) Water and cheese from the lunar desert. In *The Second Conference on Lunar Bases and Space Activities of the 21st Century,* this volume.

Haskin L. A. and Warren P. (1991) Chemistry. In *Lunar Sourcebook* (G. H. Heiken, D. T. Vaniman, and B. M. French, eds.), pp. 357-474. Cambridge Univ., New York.

Hendersen J., Yand L., and Derge G. (1961) Self-diffusion of aluminum in CaO-SiO_2-Al_2O_3 melts. *Trans. Metall. Soc. AIME, 221,* 56-60.

Henderson P., Nolan J., Cunningham G. C., and Lowry R. K. (1985) Structural controls and mechanisms of diffusion in natural silicate melts. *Contrib. Mineral. Petrol., 89,* 263-272.

Hultgren R., Desai P. D., Hawkins D. T., Gleiser M., and Kelley K. K. (1973) *Selected Values of the Thermodynamic Properties of Binary Alloys, Parts 1 and 2.* American Society for Metals, Metals Park, Ohio. 1435 pp.

Kesterke D. G. (1971) *Electrowinning of Oxygen from Silicate Rocks.* U.S. Bureau of Mines Report of Investigations 7587. 10 pp.

Lanzerotti L. J. and Brown W. L. (1981) Ice in the polar regions of the moon. *J. Geophys. Res., 86,* 3949-3950.

Laul J. C. and Papike J. J. (1980) The lunar regolith: Comparative chemistry of the Apollo sites. *Proc. Lunar Planet. Sci. Conf. 11th,* pp. 1307-1340.

Lewis R. H. (1985) Electrical conductivity measurements of high temperature silicate melts. M.A. thesis, Washington Univ., St. Louis, Missouri. 184 pp.

Lindstrom D. J. and Haskin L. A. (1979) Electrochemical preparation of useful material from ordinary silicate rocks. In *Space Manufacturing Facilities* (J. Grey and C. Krop, eds.), pp. 129-134. American Institute of Aeronautics and Astronautics, New York.

Lindstrom D. J., Haskin L. A., Semkow K. W., and Lewis R. H. (1986) Conductivities of silicate melts: Applications to lunar smelting (abstract). In *Lunar and Planetary Science XVII,* pp. 482-483. Lunar and Planetary Institute, Houston.

Mackenzie J. D. (1962) Oxide melts. *Adv. Inorg. Chem. Radiochem., IV,* 293.

Oppenheim M. J. (1968) On the electrolysis of molten basalt. *Mineral. Mag., 36,* 1104.

Osborn E. F., Devries R. C., Gee K. H., and Kraner H. M. (1954) Optimum composition of blast furnace slag as deduced from liquidus data for the quaternary system CaO-MgO-Al_2O_3-SiO_2. *Trans. AIME, 200,* 33-45.

Pearson G. L. and Bardeen J. (1949) Electrical properties of pure silicon and silicon alloys containing boron and phosphorous. *Phys. Rev., 75,* 865.

Rhodes J. M. and Hubbard N. J. (1973) Chemistry, classification, and petrogenesis of Apollo 15 mare basalts. *Proc. Lunar Sci. Conf. 4th,* pp. 1127-1148.

Rieger P. H. (1987) *Electrochemistry.* Prentice-Hall, Englewood Cliffs, New Jersey. 508 pp.

Rizzo R. A. (1976) Electrochemical studies in calcium magnesium silicate liquids. Ph.D. thesis, Univ. of Wisconsin, Madison. 203 pp.

Robie R. A. and Waldbaum D. R. (1968) *Thermodynamic Properties of Minerals and Related Substances at 198.15°K (25.0°C) and One Atmosphere (1.013 Bars) Pressure and at Higher Temperatures.* U.S. Geol. Surv. Bull. 1259.

Sack R. O., Carmichael I. S. E., Rivers M., and Ghiorso M. S. (1980) Ferric-ferrous equilibria in natural silicate liquids at 1 bar. *Contrib. Mineral. Petrol., 75,* 369-376.

Semkow K. W. and Haskin L. A. (1985) Concentrations and behavior of oxygen and oxide ion in melts of composition $CaO \cdot MgO \cdot xSiO_2$. *Geochim. Cosmochim. Acta, 49,* 1897-1908.

Semkow K. W. and Haskin L. A. (1986) *Observations on Oxide Film Formation on Platinum Electrodes During Silicate Melt Electrolysis.* McDonnell Center for the Space Sciences Report TEL-108, Washington Univ., St. Louis, Missouri.

Semkow K. W., Rizzo R. A., Haskin L. A., and Lindstrom D. J. (1982) An electrochemical study of Ni^{2+}, Co^{2+}, and Zn^{2+} ions in melts of composition $CaMgSi_2O_6$. *Geochim. Cosmochim. Acta, 46,* 1879-1889.

Simnad M. T., Derge G., and George I. (1954) Ionic nature of liquid iron-silicate slags. *J. Metals, 6,* 1386.

Weast R. C., ed. (1982) *Handbook of Chemistry and Physics,* 63rd edition, p. E-81. CRC Press, Boca Raton.

LUNAR MINING OF OXYGEN USING FLUORINE

N93-1[illegible]980

Donald M. Burt

Department of Geology
Arizona State University
Tempe AZ 85287-1404

An important aspect of lunar mining will be the extraction of volatiles, particularly oxygen, from lunar rocks. Thermodynamic data show that oxygen could readily be recovered by fluorination of abundant lunar anorthite, $CaAl_2Si_2O_8$. Fluorine is the most reactive element, and the only reagent able to extract 100% of the oxygen from any mineral, yet it can safely be stored or reacted in nickel or iron containers. The general fluorination reaction, mineral + $2F_2$ = mixed fluorides + O_2, has been used for more than 30 years at a laboratory scale by stable-isotope geochemists. For anorthite, metallic Al and Si may be recovered from the mixed fluorides by Na-reduction, and CaO via exchange with Na_2O; the resulting NaF may be recycled into F_2 and Na by electrolysis, using lanthanide-doped CaF_2 as the inert anode.

INTRODUCTION

Oxygen can be recovered from lunar rocks because they consist mostly of oxygen, by volume if not by weight. The minimum cost technology will probably be that which uses the least amount (by weight and volume) of Earth-derived plant components and reagents. The ideal reagent for oxygen recovery may be something light, reactive, and relatively nonvolatile (easily and safely storable). Hydrogen reduction of the FeO component in lunar ilmenite, $FeTiO_3$, seems currently to be the "favorite" process (e.g., *Gibson and Knudsen,* 1988), although hydrogen is highly volatile, the thermodynamics are somewhat unfavorable, and the process recovers, at best, only one-third of the oxygen in ilmenite (as water, not oxygen). High-temperature (pyrometallurgical) processes that do not require difficult radiational cooling or easily lost hydrogen (or water) thus seem preferable. Any technology will require a great deal of energy (electrical or thermal) to break the very strong metal-oxygen bonds in rocks and minerals.

THE MOST POWERFUL REAGENT: FLUORINE

Of the variety of recyclable reagents that have been suggested for lunar minerals processing (mainly combinations of hydrogen, carbon, nitrogen, chlorine, and fluorine), only one is strong enough to break all metal-oxygen bonds, releasing oxygen gas, O_2, from any rock or mineral. That reagent is simple fluorine gas, F_2, which has been used for that purpose in stable isotope laboratories for nearly 40 years (*Baertschi and Silverman,* 1951; *Taylor and Epstein,* 1962); fluorination thus constitutes a proven technology. Commonly, BrF_5 (*Clayton and Mayeda,* 1963) or ClF_3 are used in place of F_2. In either case, the fluorination of any mineral occurs rapidly at about 500°C and is safely carried out in nickel reaction vessels. The basic reaction is mineral + $2F_2$ = mixed fluorides + O_2, as discussed below.

Some other properties of fluorine are that (1) it is the lightest halogen (roughly half the atomic weight of chlorine); (2) it is inexpensive, crustally abundant, and readily extractable on Earth (*Kilgore et al.,* 1985), mainly from fluorite, CaF_2 (*Ellis and May,* 1986); (3) it is safely storable not only in Fe or Ni containers, but also as stable fluorides (salts such as sodium fluoride, NaF, which I propose to use for transporting fluorine to the Moon); (4) the fluoride ion is about the same size as the oxide ion, and thus molten fluorides easily dissolve rock oxides; (5) among halogens, fluorine forms the most stable and least volatile crystal lattices (fluorite is especially stable and therefore CaO is of potential use in "scrubbing" minor F_2 from the O_2 product); (6) fluorides have half the average bond strengths of the corresponding oxides, and consequently have lower melting temperatures (making for much easier electrolysis); (7) fluoride melts are generally nonvolatile and are much less viscous than oxide or silicate melts (with better transport properties for electrolysis); (8) silicon tetrafluoride, SiF_4, is a volatile gas (this property is useful for desilicating rocks or for concentrating Si for solar cells); (9) minor amounts of fluoride ion (as in drinking water or toothpaste) are not particularly toxic (although hydrofluoric acid, HF, and F_2 gas are); and (10) the chemistry of fluorine and of fluoride gases, crystals, and melts is well known. In particular, fluoride melts (molten cryolite) have long been used as the electrolytic solvent in aluminum production by the Hall-Heroult process (cf. *Grjotheim et al.,* 1982; *Burkin,* 1987) and were thoroughly studied as possible high-temperature reactor coolants. Fluorine gas is widely used in the processing of uranium (e.g., *Cochet-Muchy and Portier,* 1985), also a mature technology.

In sum, fluorine is the most reactive element. I believe it is indeed "the knife to cut the lunar cheese," which is a very tough and refractory one. Fluorine has been used to extract oxygen from lunar minerals for stable isotope studies since the very first (e.g., *Taylor and Epstein,* 1970; *Epstein and Taylor,* 1971). Why not extend this procedure to larger-scale oxygen extraction?

The possible use of fluorine for lunar oxygen and metal production was briefly reviewed by *Dalton and Degelman* (1972, pp. 219-220 and 225-226), but was apparently rejected essentially because "all of the reactions are very fast and difficult to control" and "because of the very corrosive nature of fluorides" (p. 220). To me, the first "disadvantage" is essentially an advantage, given proper systems design, and the second can be overcome by proper choice of container, electrode, and reagent materials, as discussed below. The above study did conclude (pp. 219 and 226) that, despite safety and corrosion problems,

the fluorination route was thermodynamically the most favorable and was the only method studied that was both anhydrous and allowed easy coproduction of metals. I might also add that it is the only one (besides direct electrolysis) that allows the direct production of oxygen as O_2 gas (instead of tied up in water, carbon monoxide, or carbon dioxide).

The direct fluorination method was considered about the same time by NASA and the U.S. Bureau of Mines (e.g., E. Schnitzer and M. James, unpublished data, 1972), but apparently has not been considered since. It is not even mentioned by *Waldron et al.,* (1979), *Waldron and Criswell* (1982), and *Waldron* (1985), who instead propose a more complex, lower temperature, hydrous procedure: the HF acid leach process, which depends on the corrosive nature of HF. Others (e.g., *Kesterke,* 1970; *Jarrett et al.,* 1980; *Anthony et al.,* 1988) have considered using molten fluorides merely as fluxes to dissolve refractory lunar oxides [property (4) above]. This parallels their 100-year use in the aluminum extraction industry. Although this use of fluorides as solvents rather than reagents also leads to the direct production of oxygen, the dry fluorination route offers many of the same advantages, and is potentially applicable to extracting oxygen from the full range of lunar minerals, including ilmenite (although I here consider only oxygen extraction from anorthite).

TYPES OF REACTIONS INVOLVING FLUORINE AND OXYGEN

The simplest reaction type involves roasting an oxide or fluoride at high temperatures to produce a metal plus oxygen or fluorine, with dissociation reactions of the type (where Me is any metal)

$$2MeO = 2Me + O_2 \qquad (1)$$

or

$$MeF_2 = Me + F_2 \qquad (2)$$

Because metal-oxygen and metal-fluorine bonds tend to be very strong, this type of reaction must, in general, be done at extremely high temperatures, and even then the oxide or fluoride may just vaporize (without dissociation). Despite the advantageous lunar vacuum, this procedure has only rarely been proposed for oxygen production (e.g., *Steurer,* 1985). Oxygen production is more readily carried out by an exchange reaction between fluorine and oxygen, of the type

$$2MeO + 2F_2 = 2MeF_2 + O_2 \qquad (3)$$

This type of reaction occurs readily over a wide range of temperatures (although Ni containment of fluorine is not practical above 500°-600°C). Note that two fluorines are needed to extract each oxygen. The shorthand notation for such an exchange operation is F_2O_{-1}, where F_2O_{-1} is a component called an "exchange operator" (*Burt,* 1974). It tells you "put two fluorines in, get one oxygen out." The operator F_2O_{-1} has properties of an electronic or Lewis acid (*Burt,* 1974; cf. *Lewis,* 1938). The implication is that the more basic the metal oxide, the more easily it can be fluorinated, releasing oxygen. Moon rocks are mainly basic (silica-poor) and therefore easy to fluorinate (*Burt,* 1988; cf. *Taylor and Epstein,* 1970).

The above reactions all involve a gas phase, potentially a problem if you want to keep your plant small, closed, and nonpolluting. Solid-solid (or solid-melt or melt-melt) reactions involving oxygen and fluorine should also be considered. The first type is an O-exchange reduction, such as

$$Ca + MgO = Mg + CaO \qquad (4)$$

You can derive such a reaction from two gaseous dissociation reactions by subtracting them so that the gas molecules cancel. In the above reaction, Ca is the reducing agent, able to reduce Mg to its metallic form because Ca has a greater affinity for (less of a tendency to give up or more of a tendency to react with) oxygen than does Mg. A similar, but slightly more complicated, reaction is

$$4Al + 3SiO_2 = 2Al_2O_3 + 3Si \qquad (5)$$

This is part of a proposed dry process for producing aluminum and silicon using a molten fluoride bath as a solvent for anorthite (*Anthony et al.,* 1988); the Al_2O_3 produced by reduction of SiO_2 is electrolyzed to Al and O_2 in a process similar to that used for aluminum production on Earth (accumulation of unreduced CaO in the melt is a problem with this method). Analogous reactions can be written for fluorides, such as

$$Ca + MgF_2 = Mg + CaF_2 \qquad (6)$$

We can similarly write

$$3Na + AlF_3 = Al + 3NaF \qquad (7)$$

and

$$4Na + Na_2SiF_6 = Si + 6NaF \qquad (8)$$

These represent the Na reduction of Al (the so-called Castner process) and of Si (*Sanjurjo et al.,* 1980) to native form, and are steps in the process proposed below.

We can also write fluorine-oxygen exchange reactions involving only condensed phases, such as

$$CaO + MgF_2 = CaF_2 + MgO \qquad (9)$$

As above, the tendency for such "two fluorines for one oxygen" exchange processes can be expressed in terms of the exchange operator F_2O_{-1} (*Burt,* 1974). As mentioned, more basic oxides have a greater tendency to become fluorinated. Of particular interest is the reaction involving the basic oxide Na_2O

$$Na_2O + CaF_2 = 2NaF + CaO \qquad (10)$$

This reaction is proposed below for moving fluorine from fluorite, CaF_2, which has a very high melting point (1418°C) and is therefore unsuitable for direct electrolysis, to NaF, whose much lower melting point (990°C) makes it more suitable for electrolysis.

ELEMENT AND EXCHANGE AFFINITIES

The general affinities of some important lunar elements for oxygen are given as a bar chart at 1000 K (727°C) in Fig. 1 (data from *Pankratz et al.,* 1984). The order at other temperatures

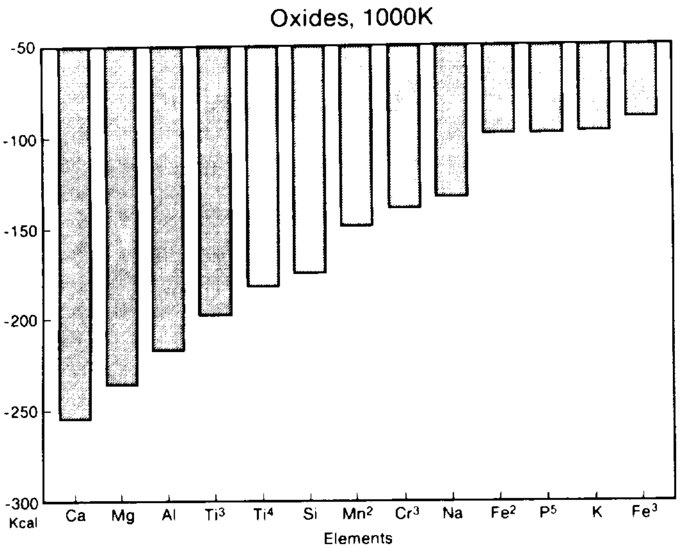


Fig. 1. Bar diagram for free energies of formation (kcal per mole of O_2) of lunar-element oxides, 1000 K. Diagram shows affinities of the lunar elements for oxygen (greatest for Ca).

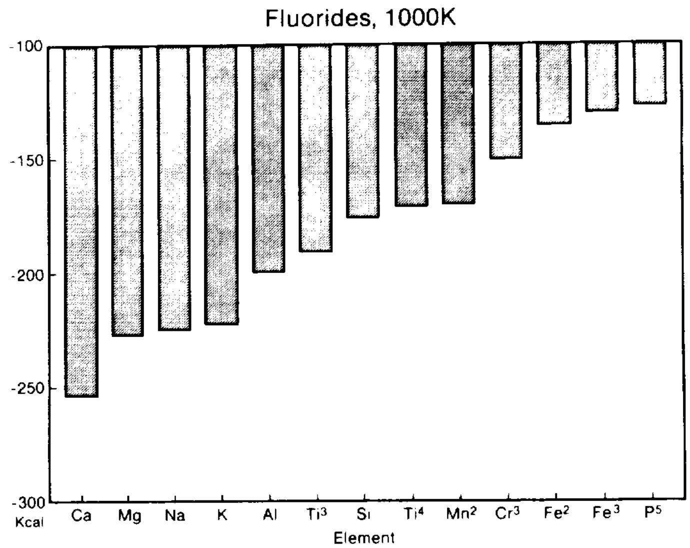


Fig. 2. Bar diagram for free energies of formation (kcal per mole of F_2) of lunar-element fluorides, 1000 K. Diagram shows affinities of the lunar elements for fluorine (greatest for Ca).

would be very similar (cf. the Ellingham or free energy vs. temperature diagrams used by extractive metallurgists; e.g., *Rosenqvist,* 1983). The general order is

$$Ca > Mg > Al > Ti^3 > Ti^4 > Si > Mn^2 > Cr^3 > Na > Fe^2 = P^5 = K > Fe^3 \qquad (11)$$

Any element to the left will reduce an element to the right from its oxide (this treatment neglects possible mixed oxides). Note that iron is very easy to reduce (a major reason why it is so widely used on Earth), and that sodium is a very poor reducing agent for oxides of elements other than iron (e.g., it cannot reduce either aluminum or silicon). Calcium is the best reducing agent, but would be the most difficult element to produce as a metal.

Affinities for fluorine are given in Fig. 2 under the same conditions. Note the different order, namely

$$Ca > Mg = Na = K > Al > Ti^3 > Si > Ti^4 = Mn^2 > Cr^3 > Fe^2 > Fe^3 > P^5 \qquad (12)$$

Sodium is now an excellent reducing agent (about the same as magnesium), and could easily reduce aluminum and silicon to metals from their fluorides (as noted above).

Affinities for F-O exchange are given in Fig. 3. Note that this is the only sequence whose order reflects position of the elements in the periodic table (e.g., the order $K > Na > Li > Ca > Mg > Be$) or periodic properties such as the charge-to-radius ratio of the cations (*Burt,* 1988). In fact, this is an order of increasing oxide acidity

$$K > Na > Ca > Mg > Mn^2 > Ti^3 > Al > Si > Fe^2 > Fe^3 > Cr^3 > Ti^4 > P^5 \qquad (13)$$

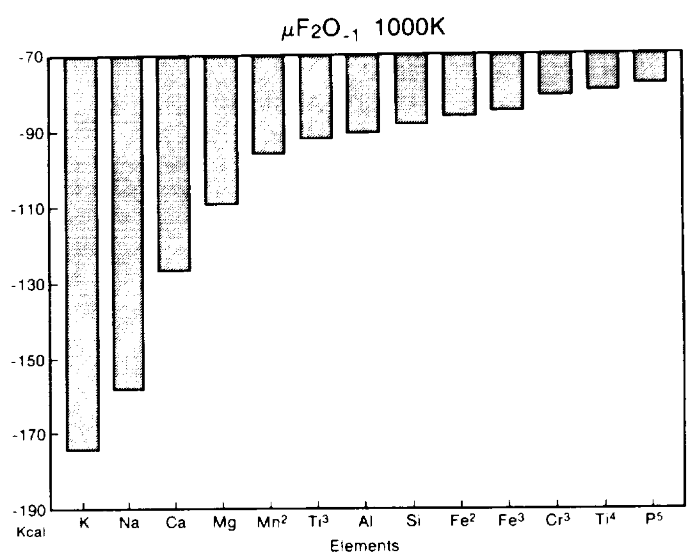


Fig. 3. Bar diagram for molar free energy differences (μF_2 -1/2 μO_2, where μ is the chemical potential) of lunar elements, 1000 K. Diagram shows affinities of the lunar elements for F-O exchange (greatest for K).

It implies, as mentioned above, that Moon rocks, being relatively basic, should fluorinate easily (releasing oxygen) and potassium or sodium oxides could be used to remove the fluorine from fluorite.

All the above information can be shown on a single μF_2 vs. μO_2 diagram, Fig. 4, where μ is the molar free energy (or chemical potential) of the gas in equilibrium with the element, fluoride, or oxide. The order of affinity for F_2 is given along the

vertical axis, that for O_2 along the horizontal axis, and that for the exchange operator F_2O_{-1} perpendicular to the diagonal lines (of slope + 1/2) from lower right to upper left.

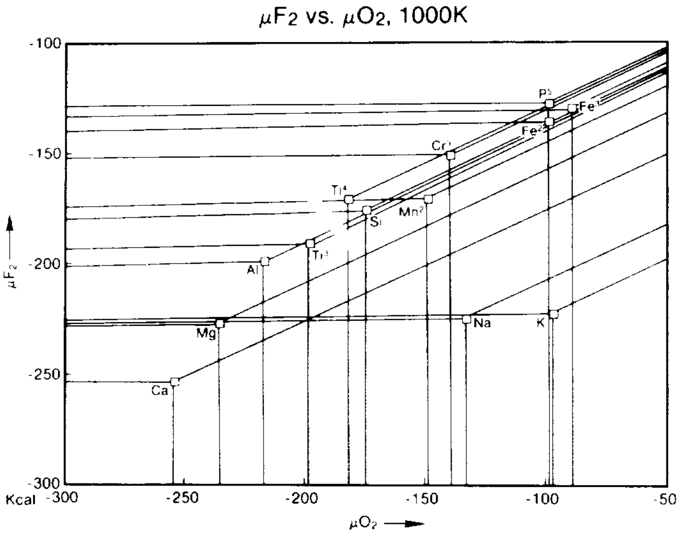


Fig. 4. μF_2 - μO_2 diagram for lunar elements, 1000 K.

STEPWISE FLUORINATION OF ANORTHITE

Although fluorination of bulk lunar soil would be possible and would yield oxygen (e.g., *Epstein and Taylor,* 1971; *Waldron,* 1985), it seems preferable to use instead a single mineral of fairly simple constitution. This facilitates metal co-recovery and recycling of the fluorine. Anorthite from lunar anorthosites is abundant, presumably could be prepared as a uniform concentrate, and could supply as by-products CaO, Al, and Si. Its idealized formula is $CaAl_2Si_2O_8$ (with minor solid solution towards albite, $NaAlSi_3O_8$).

The details of fluorinating a single mineral are more complicated than simple element affinities might indicate. A possible sequence of fluorination reactions for anorthite (as deduced from available thermodynamic and phase equilibrium data) is given below (note that an "index fluoride" is produced at each step—fluorite, topaz, Ca_2AlF_7, $CaAlF_5$, AlF_3, and finally SiF_4 gas)

$$\underset{\text{Anorthite}}{CaAl_2Si_2O_8} + 2F_2 = \underset{\text{Fluorite}}{2CaF_2} + \underset{\text{Al-silicate}}{Al_2SiO_5} + \underset{\text{Quartz}}{SiO_2} + O_2 \tag{14}$$

$$\underset{\text{Al-silicate}}{Al_2SiO_5} + F_2 = \underset{\text{Topaz}}{Al_2SiO_4F_2} + 1/2O_2 \tag{15}$$

$$\underset{\text{Fluorite}}{4CaF_2} + \underset{\text{Topaz}}{Al_2SiO_4F_2} + 2F_2 = 2Ca_2AlF_7 + \underset{\text{Quartz}}{SiO_2} + O_2 \tag{16}$$

$$2Ca_2AlF_7 + \underset{\text{Topaz}}{Al_2SiO_4F_2} + 2F_2 = 4CaAlF_5 + \underset{\text{Quartz}}{SiO_2} + O_2 \tag{17}$$

$$\underset{\text{Topaz}}{Al_2SiO_4F_2} + 2F_2 = 2AlF_3 + \underset{\text{Quartz}}{SiO_2} + O_2 \tag{18}$$

$$\underset{\text{Quartz}}{SiO_2} + 2F_2 = \underset{\text{Gas mixture}}{SiF_4 + O_2} \tag{19}$$

The overall (bulk) reaction is then

$$\underset{\text{Anorthite}}{CaAl_2Si_2O_8} + 8F_2 = \underset{\text{Mixed fluorides}}{CaAlF_5 + AlF_3} + \underset{\text{Gas mixture}}{2SiF_4 + 4O_2} \tag{20}$$

At equilibrium, the above would be the sequence of reactions occurring from top to bottom of a fixed- or fluidized-bed reactor in which sieved anorthite was fed into the top and F_2 gas into the bottom. Note that quartz is produced by each of the reactions except the last (which is the only reaction that produces a gas other than O_2) and that SiO_2, as the most acid oxide, is the most difficult to fluorinate (consistent with what was stated about exchange affinities above). The separation of SiF_4 and excess F_2 from the O_2 product, and the electrolytic recycling of the fluorides into F_2, are discussed below.

These reactions can also be seen on a barycentric triangular oxide diagram CaO-Al_2O_3-F_2O_{-1}, which is projected through the composition of (shows phases in equilibrium with) SiO_2 or quartz (Fig. 5). The six reactions (equations 14-19) above correspond to the six numbered triangular fields of the main triangle. The arrows indicate the reaction path of increasing fluorination, from anorthite towards the F_2O_{-1} corner.

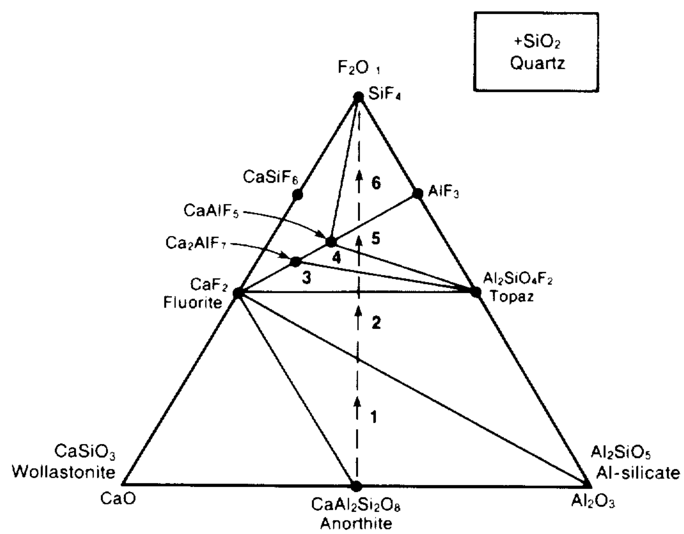


Fig. 5. Stepwise fluorination of anorthite. Triangular diagram showing phases in equilibrium with quartz. Numbered triangular fields 1 to 6 correspond to the six reactions in equations (14) to (19) in the text.

DETAILS OF THE PROPOSED PROCESS

The anorthite concentrate is fluorinated in at least two steps (probably in different parts of the same column reactor). The first step is partial fluorination of pure anorthite, using the F_2-O_2 mixture produced by the main stage of the process [equations (22) and (23) below]. Because this step removes excess F_2 from product O_2, it is a "scrubbing" step. A typical reaction is

$$CaAl_2Si_2O_8\ (\text{excess}) + 2F_2\ (\text{in } F_2\text{-}O_2 \text{ gas mix}) \rightarrow$$

$$CaF_2 + Al_2SiO_4F_2 + SiO_2 + O_2(g) \tag{21}$$

Final removal of trace F_2, should it prove necessary to produce a breathable O_2 product (for propellant use the absolute purity would be unimportant), is done as in equation (28) below.

The next or main step is complete fluorination of the fluorite-bearing product of equation (21). By using excess F_2, this step produces a mixture of leftover F_2, O_2, and SiF_4. The reaction is

$$CaF_2 + Al_2SiO_4F_2 + SiO_2 + 6F_2\ (\text{in excess}) \rightarrow$$

$$CaAlF_5 + AlF_3 + 2SiF_4(g) + 3O_2(g) \tag{22}$$

The SiF_4 from the product gas mixture of equation (22) is scrubbed using NaF to produce Na_2SiF_6, then the partly purified gas mixture (no SiF_4) is fed back to fresh anorthite to scrub the F_2 [equation (21) above]. The SiF_4-scrubbing reaction is

$$2SiF_4\ (\text{in } O_2\text{-}F_2\text{-}SiF_4 \text{ gas mix}) + 4NaF \rightarrow 2Na_2SiF_6 \tag{23}$$

Next, Si is produced by Na-reduction of the Na_2SiF_6 (and used for, e.g., solar cells)

$$2Na_2SiF_6 + 8Na \rightarrow 2Si + 12NaF \tag{24}$$

[Recycle four of the NaFs to equation (23) above; the eight remaining NaFs go to the electrolysis cell of equation (29) below.]

Analogously, Al is produced by Na-reduction of the $CaAlF_5$-AlF_3 mixture given by equation (22)

$$CaAlF_5 + AlF_3 + 6Na \rightarrow CaF_2(c) + 2Al(l) + 6NaF(l) \tag{25}$$

[Move the six NaFs to the electrolysis cell of the step in equation (29).] Some of the Na produced by electrolysis is reacted with O_2 to produce Na_2O

$$2Na + 1/2O_2 \rightarrow Na_2O \tag{26}$$

This Na_2O is used to recover F from CaF_2, producing CaO

$$CaF_2 + Na_2O \rightarrow CaO + 2NaF\ (\text{to electrolysis cell}) \tag{27}$$

If necessary, some of this CaO is used to scrub the final traces of F_2 from the O_2 product of equation (21)

$$(\text{trace})\ F_2\ (g) + CaO \rightarrow CaF_2 + O_2\ (g) \tag{28}$$

This CaF_2 is periodically recycled to the step shown in equation (27). Note that Na_2O itself should be even more effective than CaO at scrubbing traces of F_2, but I am assuming that the process will yield "waste" CaO, easily spared for this purpose (unlike Na_2O).

Finally, the NaF generated in the steps shown in equations (24), (25), and (27) above is recycled to Na and F_2 via electrolysis

$$16NaF(l) \rightarrow 16Na(l) + 8F_2(g) \tag{29}$$

This electrolysis step represents unproven technology; the main challenge is to find an electrode material that will not be attacked by the F_2 produced at the anode (fluorine will attack nearly any conventional conductor, including platinum and other precious metals). Lanthanide- or even sodium-doped fluorite, CaF_2, is a fairly good electrical conductor (e.g., *Catlow*, 1985; *Tressaud*, 1985) and is therefore a potential inert electrode material (*Burt*, 1988). It has a high melting point and won't dissolve in the molten NaF if the bath is a mixture of CaF_2 at its saturation concentration and NaF, rather than pure NaF. This procedure would, moreover, lower the minimum bath temperature from 990°C for pure NaF to 818°C for the eutectic binary mixture, thereby assisting electrolysis. A bath consisting of a ternary eutectic with LiF could have an even lower temperature of 615°C (*Barton et al.*, 1959, reproduced in *Levin et al.*, 1964, Fig. 1544). Essentially pure Na should be produced at the cathode, inasmuch as Ca and Li are much better reducing agents than Na in fluoride baths. The process itself would result in the production of huge quantities of fluorite, CaF_2, so that fluorite use as an electrode (and perhaps container) material is certainly appealing, if as yet untested.

Omitting recycled Na and F, the overall reaction is

$$CaAl_2Si_2O_8 \rightarrow CaO + 2Al + 2Si + 7/2\ O_2 \tag{30}$$

For each mole of anorthite to be processed, the plant is required to contain 20 moles of NaF (16 for electrolysis, 4 for scrubbing SiF_4), plus a large electric capacity. From formula weights, each ton of anorthite to be treated per cycle would then require 3.02 tons of NaF to be brought from Earth. Also bringing LiF and CaF_2 would lower the temperature of the electrolysis cell; these components would afterward be nonparticipating.

One could save on weight (only 1.86 tons LiF per ton capacity of anorthite) and obtain a better reducing agent by using LiF and Li for all the above processes (*Burt*, 1988). Electrolysis of a CaF_2-LiF eutectic mixture ($T = 773°C$) would, however, probably produce a Ca-rich Li alloy at the cathode, inasmuch as Li is nearly as good a reducing agent as Ca. This might offer a route to obtaining Ca-metal rather than CaO as a product of the process, given a method of separating the Ca from the Li in the alloy. Also Li, unlike Na, will reduce Mg in fluorides obtained from olivine or pyroxene, and would therefore offer a route to obtaining oxygen and metals from these minerals.

SUMMARY AND CONCLUSIONS

The proposed process basically involves stepwise fluorination of anorthite to release O_2, then Na-reduction of the mixed fluorides to the metals Al and Si, leaving CaO unreduced. In general, this is a dry, much simpler, high-temperature analog of *Waldron's* (1985 and earlier references) HF acid-leach process. The product gas is cleansed of SiF_4 by NaF and of excess F_2 by reaction with fresh anorthite (then CaO, if needed). From $CaAl_2Si_2O_8$, the process produces CaO, 2Al, 2Si, and $7/2O_2$ (i.e., 87.5% recovery of oxygen). Fluorine is brought from Earth as NaF. An unproven technology is the electrolysis of molten NaF to regenerate F_2 and Na, using doped CaF_2 as the anode. To save weight, or for treatment of Mg-bearing minerals, one could consider analogous processes with LiF in place of NaF. Gaseous F_2 produced by electrolysis is reacted immediately to produce oxygen and no fluorine need be stored or handled outside the plant.

The exact geometry and nature of the eight reaction vessels (one per numbered step) required for such a process are not yet worked out, and most of the reactions are untested, even in the laboratory, although the fluorination reactions of equations (21) and (22) are tested in stable isotope laboratories every day. Some of the reactions might best be carried out in molten fluoride

baths, others in the gas phase. Gas-solid reactions could be carried out in vertical fixed- or fluidized-bed reactors, with opposing ("counter-current") flows of gases and solids.

The main problem that I see with this process, other than its unproven technology, is that it requires considerable materials handling—multiple steps in up to eight different reaction vessels. Nevertheless, the steps might be fully automated, especially if the reactions occur fast enough. The first step in testing the feasibility of the process would be to investigate the electrolysis of molten NaF (and then of various eutectic compositions involving CaF_2 and LiF), using doped CaF_2 or finding other inert electrode (and container) materials.

Acknowledgments. R. Clayton, P. Knauth, and D. Rumble are thanked for useful discussions of fluorination reactions, D. Barron for drafting the figures, and R. Keller, L. Taylor, and an anonymous reviewer for their help with condensing the final paper. This work was mainly performed while the author was a Visiting Scientist at the Lunar and Planetary Institute, Houston, which is operated by the Universities Space Research Association under Contract No. NASW-4066 with the National Aeronautics and Space Administration. This paper is Lunar and Planetary Institute Contribution No. 748.

REFERENCES

Anthony D. L., Cochran W. C., Haupin W. E., Keller R., and Larimer K. T. (1988) Dry extraction of silicon and aluminum from lunar ores (abstract). In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century,* p. 8. Lunar and Planetary Institute, Houston.

Baertschi P. and Silverman S. R. (1951) The determination of relative abundances of the oxygen isotopes in silicate rocks. *Geochim. Cosmochim. Acta, 1,* 317-328.

Barton C. J., Bratcher L. M., and Grimes W. R. (1959) In *Phase Diagrams of Nuclear Reactor Materials* (R. E. Thoma, ed.), p. 29. Oak Ridge National Laboratory Rept. 2548.

Burkin A. R., ed. (1987) *Production of Aluminium and Alumina.* Society of Chemical Industry, Critical Reports on Applied Chemistry, 20. Wiley, New York. 241 pp.

Burt D. M. (1974) Concepts of acidity and basicity in petrology—the exchange operator approach. *Geol. Soc. Am. Abstr. with Program, 6,* 674-676.

Burt D. M. (1988) Lunar production of oxygen and metals using fluorine: Concepts involving fluorite, lithium, and acid-base theory (abstract). In *Lunar and Planetary Science XIX,* pp. 150-151. Lunar and Planetary Institute, Houston.

Catlow C. R. A. (1985) Defects in solid fluorides. In *Inorganic Solid Fluorides. Chemistry and Physics* (P. Hagenmuller, ed.), pp. 259-273. Academic, New York.

Clayton R. N. and Mayeda T. K. (1963) The use of bromine penta-fluoride in the extraction of oxygen from oxides and silicates for isotopic analysis. *Geochim. Cosmochim. Acta, 27,* 43-52.

Cochet Muchy B. and Portier J. (1985) Industrial use of inorganic fluorides. In *Inorganic Solid Fluorides. Chemistry and Physics* (P. Hagenmuller, ed.), pp. 565-605. Academic, New York.

Dalton C. and Degelman L. O., Study Managers (1972) *Design of a Lunar Colony.* NASA/ASEE Systems Design Institute. 506 pp.

Ellis J. F. and May G. F. (1986) Modern fluorine generation. *J. Fluorine Chem., 33,* 133-147.

Epstein S. and Taylor H. P. Jr. (1971) $^{18}O/^{16}O$, $^{30}Si/^{28}Si$, D/H and $^{13}C/^{12}C$ ratios in lunar samples. *Proc. Lunar Sci. Conf. 2nd,* pp. 1421-1441.

Gibson M. A. and Knudsen C. W. (1988) Lunar oxygen production from ilmenite (abstract). In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century,* p. 94. Lunar and Planetary Institute, Houston.

Grjotheim K., Krohn C., Malinovsky M., Matiasovsky K., and Thonstad J. (1982) In *Aluminum Electrolysis, 2nd ed., Fundamentals of the Hall-Heroult Process.* Aluminium-Verlag GmbH, Dusseldorf, FRG. 443 pp.

Jarrett N., Das S. K., and Haupin W. E. (1980) Extraction of oxygen and metals from lunar ores. In *Extraterrestrial Materials Processing and Construction* (D. R. Criswell, Project Director), pp. 255-267. Final Report to NASA/JSC, Houston.

Kesterke D. G. (1970) Electrowinning oxygen from silicate rocks. In *Proceedings of the 7th Annual Working Group on Extraterrestrial Resources,* pp. 139-144. NASA SP-229.

Kilgore C. C., Kraemer S. R., and Bekkala J. A. (1985) *Fluorspar Availability—Market Economy Countries and China.* U.S. Bur. Mines Inf. Circ. 9060. 57 pp.

Levin E. M., Robbins C. R., and McMurdie H. F., compilers (1964) *Phase Diagrams for Ceramists.* American Ceramic Society, Columbus, Ohio. 601 pp.

Lewis G. N. (1938) Acids and bases. *J. Franklin Inst., 226,* 293-313.

Pankratz L. B., Stuve J. M., and Gokcen N. A. (1984) *Thermodynamic Data for Mineral Technology.* U.S. Bureau of Mines Bull. 677. 355 pp.

Rosenqvist T., ed. (1983) *Principles of Extractive Metallurgy,* 2nd ed. McGraw-Hill, New York. 506 pp.

Sanjurjo A., Nanis L., Sancier K., and Bartlett, R. (1980) Production of solar grade Si by the Na reduction of silicon fluoride compounds (abstract). In *Extraterrestrial Materials Processing and Construction* (D. R. Criswell, Project Director), p. 237. Final Rept. to NASA/JSC, Houston.

Steurer W. H. (1985) Lunar oxygen production by vapor phase pyrolysis. In *Space Manufacturing 5* (Proc. 7th Princeton Conf.), pp. 123-131. American Institute of Astronautics and Aeronautics, New York.

Taylor H. P. Jr. and Epstein S. (1962) Relationship between O^{18}/O^{16} ratios in coexisting minerals of igneous and metamorphic rocks. Part 1: Principles and experimental results. *Geol. Soc. Am. Bull., 73,* 461-480.

Taylor H. P. Jr. and Epstein S. (1970) O^{18}/O^{16} ratios of Apollo 11 lunar rocks and minerals. *Proc. Apollo 11 Lunar Sci. Conf.,* pp. 1613-1626.

Tressaud A. (1985) Electronic conduction in fluorides. In *Inorganic Solid Fluorides. Chemistry and Physics* (P. Hagenmuller, ed.), p. 415-422. Academic, New York.

Waldron R. D. (1985) Total separation and refinement of lunar soils by the HF acid leach process. In *Space Manufacturing 5* (Proc. 7th Princeton Conf.), pp. 132-149. American Institute of Astronautics and Aeronautics, New York.

Waldron R. D. and Criswell D. R. (1982) Materials processing in space. In *Space Industrialization* (B. O'Leary, ed.), pp. 97-130. CRC Press, Boca Raton, Florida.

Waldron R. D., Erstfeld T. E., and Criswell D. R. (1979) Overview of methods for extraterrestrial materials processing. In *Space Manufacturing III* (Proc. 4th Princeton Conf.), pp. 113-127. American Institute of Astronautics and Aeronautics, New York.

USES OF LUNAR SULFUR

N93-1 981

D. Vaniman, D. Pettit*, and G. Heiken

*EES-1 (*M-9)*
Los Alamos National Laboratory
Los Alamos NM 87545

Sulfur and sulfur compounds have a wide range of applications for their fluid, electrical, chemical, and biochemical properties. Although known abundances on the Moon are limited (~0.1% in mare soils), sulfur is relatively extractable by heating. Coproduction of sulfur during oxygen extraction from ilmenite-rich mare soils could yield sulfur in masses up to 10% of the mass of oxygen produced. Sulfur deserves serious consideration as a lunar resource.

INTRODUCTION

Volatile constituents such as molecular oxygen, nitrogen, water, and hydrocarbons are rare on the Moon. The absence of such molecules is one of the problems that confronts prolonged lunar exploration or permanent lunar bases. The lightweight compounds of the elements from hydrogen to oxygen are vital for life, and many of these elements play important roles as fuels, solvents, and industrial chemicals in processes that have become the necessities of industrialized life on Earth. The scarcity of these elements on the Moon thus raises two barriers against easy expansion into space: one against the simple need to stay alive and the other against easy transplantation of Earthbound industrial processes.

With imagination this assessment need not be so bleak. Living in space will require adaptation, but it also opens opportunities to reassess the ways in which we live and use available resources. Sulfur on the Moon may well prove a satisfactory replacement for lighter volatile elements and their compounds in some applications. It may even open new possibilities and uses that surpass a mere duplication of what is already done on Earth.

Our present knowledge of lunar samples suggests that the best place to collect sulfur on the Moon is from mare soils and rocks. Although sulfur is not so abundant that it is available without effort, it does rank eleventh in weight abundance among the elements in average lunar mare rocks. *Gibson and Moore* (1974) found that the high-Ti mare basalts, in particular, have high sulfur contents, in the range of 0.16% to 0.27% by weight. These authors also make the important point that lunar basalts actually have more sulfur than terrestrial basalts, which seldom have more than 0.15%.

Although terrestrial basalts are relatively low in dispersed sulfur content, this sulfur is extracted and concentrated by circulation of heated water. This process results in the remarkable sulfur-rich environments at midocean spreading ridges, where base-metal sulfides are deposited in great abundance and "unearthly" sulfur-metabolizing organisms proliferate. Clearly, we cannot expect heated water to have concentrated sulfur on the Moon. The relatively high sulfur content of lunar mare basalt 12036, however, led *Gibson et al.* (1977) to speculate on the possibility of Fe-FeS liquid segregation and accumulation in some mare magmas. Discovery of sulfur-rich ore bodies on the Moon would be a major find that could accelerate exploitation immensely, but until their existence is actually proven, it would be unwise to plan on their use.

Another possible means for natural concentration of lunar sulfur may be vapor transport and deposition; the abundance of sulfur in volatile coatings on lunar pyroclastic glass droplets strongly suggests that sulfur was involved as a propellant gas in fire-fountain types of eruptions (*Butler and Meyer,* 1976). However, the analyses of volatile coatings on glass droplets suggest that significant amounts of sulfur are lost rather than trapped on droplet surfaces as a result of pyroclastic eruption. For example, the sulfur contents of the famous pyroclastic "orange glass" deposit of Shorty crater at Apollo 17 contains only 0.06-0.08% sulfur (*Gibson and Moore,* 1974), whereas comparable chilled Apollo 17 lavas retain more than 0.16% sulfur. Unless geologic traps for volatile sulfur are found on the Moon (perhaps in vesicle pipes or lava tubes?), there is reason to believe that lunar volcanic gases have acted more effectively in the dispersal of sulfur than in its concentration. The formation of soil on top of sulfur-rich lava flows also results in decreased sulfur content, through the combined processes of sulfur volatilization by small meteoritic impacts and of dilution by addition of sulfur-poor highland materials (*Gibson and Moore,* 1973, 1974). For practical purposes, the ranking of sulfur contents presently known in lunar samples is about as shown in Table 1.

TABLE 1. Sulfur in lunar samples.

Rock or Soil Type	Sulfur Content (wt%)
High-Ti mare basalts (A-17)	0.16-0.27 (avg 0.21)
Low-Ti mare basalts (A-12)	0.06-0.15 (avg 0.11)
High-Ti mare soils (A-17)	0.06-0.13 (avg 0.10)
Low-Ti mare soils (A-15)	0.05-0.06 (avg 0.05)
Highland rocks (A-16)	0.01-0.14 (avg 0.07)
Highland soils (A-16)	0.03-0.09 (avg 0.06)

Data from *Gibson and Moore* (1973, 1974), *Gibson et al.* (1977), *Kerridge et al.* (1975), and *LSPET* (1972). Note that the ranges and averages cited are for specific Apollo sites (12, 15, 16, and 17); the data include possible analytical differences between laboratories.

Although the richest known sources of sulfur are the high-Ti mare basalts, extraction of this sulfur would require energy-intensive crushing of hard rock. Most of the sulfur in the basalts occurs as sulfide in the mineral troilite (FeS). The easiest source of sulfur is high-Ti mare soils, which need not be crushed prior to processing. In addition to the sulfur in troilite, some surface-correlated sulfur can be found in soil samples. In pyroclastic soils, surface-correlated metal sulfides probably occur (*Butler and*

Meyer, 1976; *Cirlin and Housley,* 1979), but sulfur may also occur as metal sulfates that are readily volatilized to produce SO_2 (D. McKay, personal communication, 1988). The heating experiments of *Gibson and Moore* (1973) on Apollo 15 and 16 samples indicate that 12-30% of the total soil sulfur can be extracted at 750°C, 50-70% of the total sulfur is extracted at 950°C, and 85-95% of the total sulfur is extracted at 1100°C (vacuum conditions, $<2 \times 10^{-6}$ torr). *Gibson and Moore* (1974) suggest that the 12-30% of the sulfur extracted at 750°C is surface correlated. Most of the higher temperature sulfur is probably derived from troilite. The sulfur is given off as SO_2 and H_2S, which *Gibson* (1973) attributes mainly to reaction between troilite and other phases at high temperatures.

Sulfur is not the only volatile element to be won. Heating of typical lunar soils will be useful in the cogeneration of small amounts of hydrogen (about 0.001-0.020%), helium (0.001-0.006%), carbon (0.001-0.028%), and nitrogen (0.001-0.016%) that are the solar-wind constituents of lunar fines (*Williams and Jadwick,* 1980). Heating of high-Ti pyroclastic deposits to 1200°C will also provide some cogeneration of Zn (0.01-0.03%), Na, K, Cl (0.002-0.010%), F (0-0.02%), and other vapor-transported elements (*Cirlin and Housley,* 1979; *Butler and Meyer,* 1976; *Meyer et al.,* 1975).

Thus, although sulfur is not richly concentrated on the Moon, it is present in sufficient abundance and associated with other potentially useful elements that make the mining of lunar sulfur worth serious consideration. However, this consideration will not go very far if there is not a well-established set of end uses for the sulfur and its codeposited elements. Sulfur has a broad range of chemical and physical properties that may make it extremely useful. Perhaps most importantly, sulfur and sulfur compounds have the capacity to substitute for water in many aqueous-based mechanical and chemical processes on Earth. Sulfur research is so broad and diverse that we cannot fully cover its terrestrial applications in this short paper. Moreover, we can only begin to speculate on the possible uses of sulfur in space. Our purpose is rather to suggest several starting points for more imaginative studies on the uses of lunar sulfur. These starting points are discussed below under three broad categories: (1) the use of sulfur fluid and physical properties, (2) the use of sulfur electrical properties, and (3) the use of sulfur chemical and biochemical properties.

THE USE OF SULFUR FLUID AND PHYSICAL PROPERTIES

Pure sulfur is fluid over a broad range of temperatures. Depending on crystal form, sulfur melts at 112.8°C (orthorhombic) or 119°C (monoclinic; *Weast,* 1982). Although the liquid does not boil until 444.6°C, it begins to lose its low-temperature fluidity and become very viscous at about 160°C. Figure 1 shows the variability of viscosity with temperature. At average lunar daytime temperatures (~107°C) minimal heat input would maintain sulfur as a low-viscosity liquid. At the maximum lunar equatorial daytime temperature (123°C) no additional heat would be necessary to keep sulfur molten.

Sulfur Concrete

A direct application of liquid sulfur on the Moon would be in the production of sulfur concrete (*Crow and Bates,* 1970). Sulfur concrete has found many applications on Earth and is being used in areas where corrosion resistance is important or in extreme

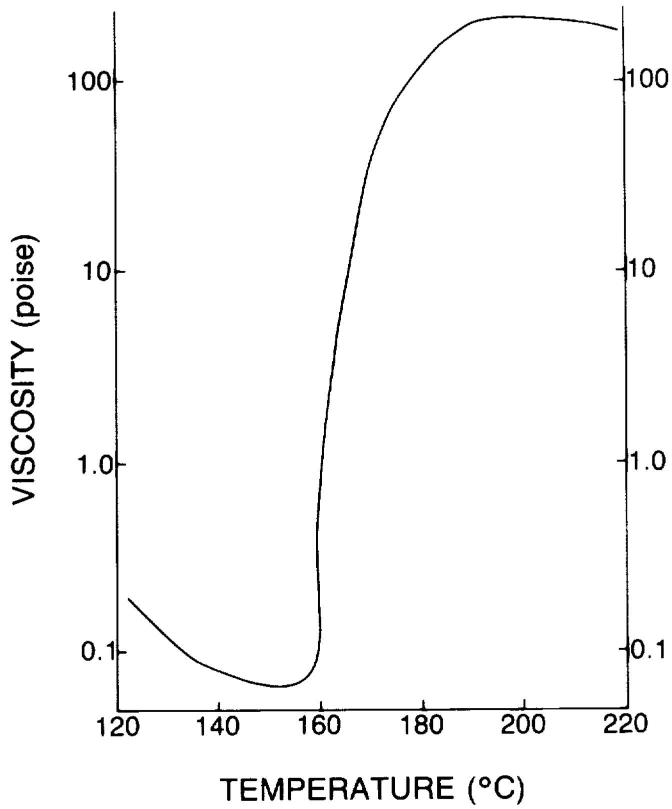


Fig. 1. Viscosity of liquid sulfur (gas free) as a function of temperature (data from *Weast,* 1982).

desert environments (*Sulphur Institute,* 1979). A particular advantage of sulfur concrete on the Moon is that it needs no water in its production and is best poured hot at temperatures of 125° to 140°C, which are only slightly higher than the average lunar daytime temperature. Contrasted with water-based concrete, sulfur concrete attains most of its final strength within hours rather than weeks and has more than twice the compressive and tensile strength. Weight ratios of sulfur to aggregate are approximately 1:3, so that the amount of sulfur concrete produced could be about four times the amount of sulfur mined on the Moon. Thermal stability is a concern; *Crow and Bates* (1970) suggest that sulfur concrete be used only in buried structures on the Moon where full-sun thermal exposure will not be a problem.

Sulfur Sealants

Lunar habitats must be capable of maintaining a pressurized atmosphere. Some redundancy in sealants to contain the atmosphere is desirable, and a method of spray-impregnating walls of regolith or the internal surfaces of lava tubes might be useful. Thioelastomers (thiokols) can be mixed with small amounts of molten sulfur to make extremely tough materials (*Leclercq,* 1972). The production requirements of hard or rubbery coatings are presently too complex for simple extension to the Moon, but imaginative use of organic waste with lunar sulfur might produce a useful sealant.

Sulfur Dioxide for Fluid Uses

As noted in the introduction, *Gibson* (1973) found that most sulfur released from lunar samples by heating in vacuum is not released as S but as SO_2 or H_2S. Contrasted with pure sulfur, SO_2

has a more useful range of fluid properties and has physical-chemical properties that can fit special fluid-application requirements. Sulfur dioxide is liquid between -75.52°C and -10.08°C, with corresponding viscosities between 0.0068 and 0.0043 poise. This liquid is a polar solvent, although its dipolar attractive field is weaker than that of water. Where water is an excellent solvent for strong dipoles, liquid SO_2 is a better solvent for nonpolar or easily polarized molecules. Sulfur dioxide is a good solvent for halogens and for olefinic and aromatic hydrocarbons, but it is a poor solvent for aliphatic hydrocarbons (*Burow*, 1970). The halogens are quite soluble in liquid SO_2; metal chlorides are highly soluble and this property may be particularly important on the Moon. There is strong evidence that many of the metals with high boiling points (e.g., Zn and Ga) that are found on the surfaces of lunar pyroclastic particles were transported and deposited as more volatile metal chlorides (*Meyer et al.*, 1975). If this is the case, then these deposits might be easily stripped and collected from pyroclastic deposits using an SO_2 washing process.

There are many potential uses of SO_2 as a fluid. Some attractive possibilities are in refrigerant systems, in turbines (Rankine cycle), in heat transfer systems (liquid phase), in heat pipes (gas phase), in slurry lines for regolith or waste transport, and in hydraulic systems. Availability of SO_2 will open a broad range of possibilities for controlling energy and materials on the Moon. An important caveat in the use of SO_2, however, is its extreme toxicity. The fluids in use would have to be isolated from habitats.

THE USE OF SULFUR ELECTRICAL PROPERTIES

Sulfur, especially in Na-S combinations, has potential use in both solar energy collection systems and in storage batteries.

Solar Energy Conversion

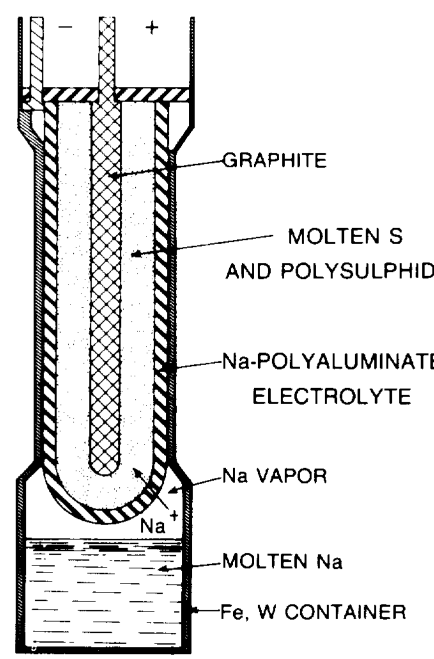
There is considerable active research into Cu_2S-based thin-film solar cells and several sulfur-bearing photoelectrochemical (PEC) cells (*Chopra and Das*, 1983). The thin-film solar cells employ a heterojunction between two metal sulfides, one of which is Cu_2S (p-junction) and the other a sulfide of Cd or ZnCd (n-junction). Such cells are still being perfected; efficiencies were around 7% in the mid 1970s but had risen to about 10% by 1981. One advantage of these cells is that they are, as the name implies, thin films of relatively light mass. The cells are layered structures, with layers as thin as a few tens or hundreds of angstroms deposited in sequence. Total thickness of the cell would typically be 5-50 μm. The efficiency of present Cu_2S/CdS cells crests at light intensities between 20 and 120 mW/cm^2, a range that includes the one-sun intensity of 50 mW/cm^2. Although the efficiency of this system is currently less than half that of some advanced photovoltaics systems now under investigation (InP or GaAs; *Flood*, 1986), there is a possible advantage in that the sulfur would not have to be imported.

In practice, the need for some material imports (mostly Cd) may be a potential problem in production of thin-film solar cells on the Moon. Most of the cell mass is Zn and Cd, and Cd is critical to efficient thin-film cells. Although there is good reason to believe that both S and Zn occur in extractable quantities in lunar pyroclastic deposits (0.07% S and 0.02% Zn; *Gibson and Moore*, 1974; *Butler and Meyer*, 1976), Cd is not comparably enriched. In addition, once the cells are produced, it is not known how well they might survive in the space environment. Still, this is an energy conversion system that is worth serious consideration. One potentially advantageous aspect of the thin film cells is the evidence that vacuum evaporation is probably the best method for cell production (*Chopra and Das*, 1983). High-vacuum systems should be relatively easy to operate in space.

An alternative approach to the use of sulfur in solar energy collection is through a photoelectrochemical (PEC) effect. Sulfur is important in the electrolyte solution as a "hole scavenger" at the photoanode. A well studied PEC cell configuration uses a CdSe photoanode with a CdS interface against an electrolyte (*Chopra and Das*, 1983). One practical electrolyte contains various proportions of Na_2S, S, and NaOH (*Russak et al.*, 1980). The cell efficiencies observed range from 3% to 8%. As with the thin film cells, a potential drawback may be the need to import Cd and, in this case, Se for lunar production. Economic study may well show that it would be more advantageous to form light photocells on Earth and export them intact to the Moon, or to rely on possible crude but rugged cells such as those that might be made out of minimally processed lunar ilmenite (*Meet et al.*, 1987).

Electrical Energy Storage

The greatest payoff in the use of indigenous lunar sulfur for electrical applications may be in the *in situ* production of relatively massive storage batteries. Sulfur-based storage batteries have widespread applications on Earth. In addition to the ubiquitous Pb-PbO_2-H_2SO_4 battery (which, unfortunately for lunar use, requires precious water), there is active research in the development of molten electrolyte Na-S storage cells for electric vehicles. These cells operate at about 300-350°C, with a two-stage discharge that derives electrons from Na-to-Na^+ oxidation by (1) $5S + 2Na \rightarrow Na_2S_5$ and (2) $3Na_2S_5 + 4Na \rightarrow 5Na_2S_3$. The discharge voltage of the cell varies with the reaction stage, from about 2.08 V for reaction (1) to 1.76 V for reaction (2) (*Bagotzky and Skundin*, 1980, pp. 320-337). The predicted cell performance for the near future is 150-200 W-hr/kg. A schematic cross section of a Na-S storage battery is shown in Fig. 2.



after Bagotzky and Skundin, 1980

Fig. 2. A molten electrolyte Na-S battery (after *Bagotzky and Skundin*, 1980).

The electrolyte for the cell is a sodium polyaluminate (with $n = 3$-11 in the formula $Na_2O.nAl_2O_3$) that is porous to Na^+. This electrolyte is formed as a ceramic and is difficult to manufacture (*Bagotzky and Skundin,* 1980); this component and the porous graphite positive electrode would probably have to be supplied from Earth. The requirement for Na as well as S may be viewed critically in terms of availability on the Moon, but there is some evidence for Na associated with the surface-deposited volatiles of lunar pyroclastic deposits (*Cirlin and Housley,* 1979). The sodium mineralogy and abundances in these deposits are poorly known, but the possible use in batteries justifies further study. Should the indigenous lunar sodium be found insufficient, a useful alternative may be to import NaOH, which could be processed after arrival to provide Na, O_2, and H_2O (all of great value on the Moon).

THE USE OF SULFUR CHEMICAL AND BIOCHEMICAL PROPERTIES

The chemical uses of sulfur are so varied that we can only touch on a few in this paper. The examples chosen are those that appear to the authors to have important potential applications on the Moon.

Sulfuric Acid

Sulfuric acid usage is a common measure of industrial capacity on Earth; this acid has so many uses that it is practically a generic guide to productivity. A large number of potential uses on the Moon might be considered, but these must be weighed against the need to consume water in the production of sulfuric acid. As one example of possible uses, the acid could be employed in thermochemical splitting of water to produce H_2 - O_2 for propellant or for fuel cells (see below). A very different example of sulfuric-acid use would be the destruction of organic waste as part of a Closed Ecological Life Support System ("CELSS"; *MacElroy et al.,* 1985). Highly concentrated sulfuric acid can remove hydrogen and oxygen from some organic compounds to produce water; simple plant sugars might be processed in this manner.

The production of sulfuric acid on the Moon might occur as a variant of the terrestrial contact process, in which SO_3 is made by catalytic oxidation of SO_2 (over platinum or vanadium pentoxide) and bubbled through relatively dilute sulfuric acid to produce concentrated acid. This process would require oxygen input to oxidize the relatively reduced sulfur that occurs in lunar regolith. Sulfuric acid can also be produced by electrolysis of SO_2 in water (see section on thermochemical water splitting, below). In a closed system the depletion of water and oxygen could be minimized, but some loss will probably be incurred and the benefits must be weighed against this loss.

Sulfuric acid production and control is almost a necessary adjunct industry if oxygen is to be produced from lunar ilmenite. Sulfur is a serious contaminant in the reduction of lunar ilmenite; H_2S and sulfur-based acids would pose serious problems through corrosion and induced electrolysis of water. The most direct way to avoid such problems would be to extract (and use) the sulfur before the ilmenite concentrates are processed for oxygen.

Thermochemical Water-Splitting

Water can be split into H_2 and O_2 for collection and cooling to provide liquid rocket propellant. On a smaller scale, water might be split for use in hydrogen fuel cells. Fuel cells may be particularly useful if the water is reclaimed at the exhaust. There are several options for producing H_2 from water on the Moon; extraction from waste methane and electrolysis of water are both possible. Thermochemical splitting of water, however, would be advantageous where reactor power is available to provide a high-temperature heat source. *Dokiya et al.* (1979) describe both an SO_2 hybrid cycle and a SO_2-H_2S cycle for thermochemical splitting of water. The SO_2 hybrid cycle uses electrolysis of $SO_2 + 2H_2O$ to produce $H_2SO_4 + H_2$, followed by thermal dissociation of the sulfuric acid at 800°-850°C to produce $H_2O + SO_2 + 1/2O_2$. The SO_2-H_2S cycle requires only heat energy (830°C) but has four steps and requires input of both H_2S and SO_2 as well as water. For lunar applications the SO_2 hybrid cycle is probably most attractive because of its relative simplicity (two steps instead of four) and the relative conservation of sulfur as SO_2 (output ideally equals input but is limited by 70-80% conversion efficiency). The most significant drawback of this method is the requirement for use of electrical as well as thermal energy.

Sulfur as a Fluxing Agent

Sulfur is used terrestrially as a fluxing agent in reducing the melting points of glasses. This use may also be practical on the Moon, where glass production may be sought for structural uses (*Blacic,* 1985). Experiments with a variety of regolith-sulfur mixtures are needed to determine the utility of such a process.

The Brimstone Rocket

Production of rocket propellants from lunar resources would be a major boon for expanded space exploration (*National Commission on Space,* 1986). There has been considerable study of systems to produce oxygen from lunar regolith, particularly from concentrates of lunar ilmenite (*Cutler and Krag,* 1985; *Gibson and Knudsen,* 1985). Lunar sources of fuels to be oxidized, however, are extremely scarce. Hydrogen is so rare that extensive use for propellant may require expensive imports, perhaps as methane or ammonia from Earth (*Friedlander,* 1985). Other fuels such as silane (SiH_4; *Rosenberg,* 1985) might be produced in part from lunar feedstocks but would still require hydrogen imports. In contrast, sulfur might provide a truly indigenous lunar fuel.

Some sulfur release will be an inevitable byproduct of lunar oxygen production. Lunar oxygen production is targeted on mare regoliths with high ilmenite content; these are also the regoliths with highest sulfur content (0.06% to 0.13%; see Table 1). In an oxygen production plant such as *Cutler and Krag* (1985) envision, the sulfur byproduct would be about 1% of the O_2 mass produced, assuming 0.1% collectable S in the ilmenite-enriched feedstock. If the tailings from ilmenite enrichment are also processed for sulfur, then the total sulfur production would be about 10% of the O_2 mass. These proportions permit serious consideration of a sulfur-oxygen propulsion system (a "brimstone" rocket).

The brimstone rocket could be fueled with liquid sulfur and liquid oxygen, the sulfur being kept between 150° and 160°C where its viscosity is lowest and it is easiest to pump. Atomized droplets of liquid sulfur would be introduced with gaseous oxygen into the combustion chamber. Here the exothermic reaction to SO_2 would liberate about 4600 kJ/kg SO_2. Isotropic expansion would result in an ideal exhaust velocity near 3000 m/sec, giving a specific impulse (I_{sp}) of ~300 sec.

The performance of the brimstone rocket would be sufficient for pogosticking from one point to another on the lunar surface or for putting payloads into lunar orbit. To place a payload into a 100-km lunar orbit requires that the initial rocket mass at launch be about 44% propellant at lift off.

The exhaust gases from the brimstone rocket would be compatible with the lunar environment. Sulfur dioxide is a condensable gas, which would ultimately be chemisorbed as coatings on the regolith rather than accumulating as a gas to increase the lunar atmosphere. In contrast, rockets based on combustion of metals and excess oxygen will liberate large quantities of oxygen into the lunar environment. This oxygen might build up to a significant atmosphere and provide oxidizing conditions that could alter the pristine state of the lunar regolith.

Sulfur for Plants, Animals, and People

Sulfur is a necessary trace element in the diets of many organisms, including people. Powdered sulfur also has uses in plant fertilization (*Leclercq,* 1972). These uses could probably be met simply by the use of unprocessed lunar soil in CELSS systems. For radiation protection, however, it is worth considering the inclusion of small-scale pharmaceutical production of sulphydryl compounds in space for advanced CELSS systems.

Because nitrogen and other inert gases will be scarce on the Moon, it is likely that the atmospheres in lunar habitats will be oxygen-rich. One consequence of this may be a long-term increase in susceptibility to sickness and biological damage from ionizing radiation (*von Sonntag,* 1987). Sulphydryl compounds are the most extensively studied and effective means of chemical prophylaxis against radiation damage (*von Sonntag,* 1987; *IAEA,* 1969). The action of these compounds is still incompletely understood, but there is considerable evidence that one of their effects is not entirely unlike the role of sulfur in photocells, where the ability of sulfur to assume a large variety of electron shell configurations will not abide an association with electron holes or active charged radicals (see section on PEC photocells, above). Energy transfer from ionizing radiation into biological materials produces target radicals, which will produce cellular damage if left "unquenched." Potentially damaging hydrogen ionization induced in a biological target can release a proton, leaving a target radical with chemical activity that may eventually result in permanent damage. The sulphydryl compounds can split rapidly to donate a replacement hydrogen before permanent damage occurs (*von Sonntag,* 1987).

The amount of sulfur in sulphydryl compounds is actually quite small. Glutathione, a well-studied example, has only one sulfur in a molecule of 37 atoms (the rest being H, O, N, and C). These compounds are not heavy users of sulfur resources, and for the near future are probably best produced on Earth even if a use is found for them in space. On the other hand, a flurry of early research into new sulphydryl compounds has now stagnated (*von Sonntag,* 1987) but might be renewed if considered in terms of the space environment. The advances made in synthesizing pharmaceuticals under microgravity conditions may be applicable to advances in chemical protection from ionizing radiation. Ultimately, the use of lunar sulfur may play a role in expanded human occupation of near-Earth space.

A sulfur-based life cycle may prove useful on the Moon. Such a cycle may be modeled on the sulfur life cycles found in midocean spreading ridges where sulfur-metabolizing bacteria support a host of higher organisms including giant tube worms, vent crabs, clams, and snails. These midoceanic life centers are unusual in that the food chain is entirely based on sulfur compounds released from volcanic fumaroles. Sunlight, the energy source that was once thought to be the sole basis of life, is absent from this deep ocean microcosm.

There are several advantages of the use of a lunar sulfur life cycle compared to photosynthesis. Such a cycle could operate without artificial light, which would be a requirement for photosynthesis-based life systems at any nonpolar lunar base over the 14-day lunar night. Artificial light may be a permanent requirement for photosynthesis if life systems have to be deeply buried for radiation shielding. The energy efficiency of making electricity into light is poor, resulting in the release of significant quantities of low-temperature heat. The photosynthetic efficiency of using light energy is also poor, resulting in the release of more low-temperature heat. Rejection of low-temperature heat on a lunar base is troublesome because it ultimately hinges on radiation into space. Radiation is inefficient at low temperatures, requiring large radiation areas or the use of heat pumps to increase the temperature of the waste heat. The heat pumps in turn will generate 8 to 10 times the original heat load, which must also be radiated away.

The sulfur life cycle is based on hydrogen sulfide as the energy source, which can be produced from lunar sulfur or recycled from the biota using chemical processes that reject waste heat at high temperatures. The oxidation of the sulfur occurs in aqueous solution where the chemical energy in hydrogen sulfide is efficiently used by the bacteria. Subterranean lava tubes or man-made tunnels could be sealed and flooded with aqueous solutions necessary to support a modified low-pressure sulfur life cycle without need for lighting. Heat transfer between the liquid solution and the tunnel walls may be sufficient to dissipate the small amounts of low-temperature waste heat. A lunar colony's need for a variety of food will certainly dictate the production of familiar photosynthetically based food chains, but the staples required to support a lunar base could well be supplemented by a sulfur-based system. Bioengineering would be required to adapt the existing high-pressure sulfur-metabolizing organisms to a low-pressure lunar system, and to produce palatable foods (unless the lunar inhabitants develop a taste for tube worms and vent crabs). Separate food systems based on photosynthesis and sulfur would provide a redundancy that could increase the security or, in crisis, ensure the survival of a large lunar colony.

PRACTICAL PRODUCTION OF SULFUR

A wide variety of schemes could be proposed for extracting sulfur from lunar rocks and soils, but not all may be cost effective or practical on the Moon. Procedures requiring multiple complex processing steps are probably too cumbersome to be practical—especially if they cannot be automated and run as autonomous systems. Heating lunar feedstocks to over 1100°C is probably one of the simplest of possible extraction procedures. Moreover, this method has already been tested and proven. *Gibson* (1973) used thermogravimetric-quadrupole mass-spectrometric analysis to determine that Apollo 14 and 15 soil samples release their sulfur as SO_2 and H_2S on heating to 1000°-1300°C. His experiments were run at vacuum conditions close to those that would be expected on the Moon. These gases are thus the sulfur products to be anticipated on simple heating of lunar feedstocks.

Some direct uses of SO_2 liquid are discussed above. Many applications of sulfur, however, would require its production as

pure S. This would be particularly true for the brimstone rocket. Fortunately, the sulfur-bearing gases that are liberated from lunar feedstocks can be combined in the Claus reaction to produce pure sulfur and water.

$$SO_2 + 2H_2S \rightarrow 2H_2O + (3/x)S_x$$

where x varies between 2 and 8. This reaction has been studied intensively and used in the treatment of SO_2 waste gases on Earth (*Pfeiffer*, 1975). The Claus reaction is of particular interest not only because it uses exactly those sulfur gases expected from lunar feedstock, but also because it produces valuable water.

Since the Moon is such a different environment, it is important to consider how terrestrial processes might be perturbed on this new industrial frontier. For example, radiolysis of SO_2 can produce small amounts of S and SO_3 (*Rothschild*, 1964). Will this effect be a problem in SO_2 liquid management, or might it be used to advantage in boosting the production of S from SO_2? Model industrial processes must be considered in terms of the environment where they will be used, and in many cases may require small pilot-plant tests on the Moon before full-scale production is sought.

Finally, sulfur production should not be viewed as an alternative to the extraction and use of other gases (such as O_2, H_2, and He) on the Moon. Schemes for extracting one of these gases will often provide some of the others as well. Each gas has its own set of uses, and thus a special value for exploitation in space. Extraction schemes that combine cogeneration with multiple uses will obtain the maximum benefit and minimum wastage of these rare lunar resources.

CONCLUSIONS

It is fortuitous to find small but useful amounts of extractable sulfur on the Moon. In an environment devoid of gas-forming elements, sulfur has the potential to provide as significant an impact on lunar development as coal and petroleum had for the industrialization of society on Earth.

Even at its low abundance in lunar regolith, the ~0.1% of sulfur available across many thousands of square kilometers of high-Ti mare regolith may be useful. Thermal processing of mildly crushed regolith from high-Ti basaltic lava areas at 1100°C could yield about 1000 kg of sulfur from a patch of regolith 100 m × 100 m and 10 cm deep. Figure 3 shows the possible scars that would be left by much more extensive mining in two types of regolith at the Apollo 17 site. Each scar has an area of about 10 km^2, but patch A would produce ~1,000,000 kg of sulfur from high-Ti basaltic lava regolith, whereas patch B would produce ~700,000 kg of sulfur with cogeneration of the metals and sodium that occur on the surfaces of pyroclastic glasses. Either patch would produce sufficient sulfur to lift a payload of several hundred metric tons off the Moon using the brimstone rocket.

In practice these patches would not be nearly so regular or well contained; patch A in particular would have to be gerrymandered to avoid large craters in the basaltic lava regolith (the pyroclastic mantle is much smoother, and crater avoidance would be less of a problem in patch B). It is possible that these mined areas would not leave visible scars. The most efficient extraction system could be a mobile processing plant that would return more than 99% of the processed regolith and leave no trench. Such a system would be merely one more gardening event at the lunar surface. The depth of excavation would be strongly process dependent (considering plant mobility vs. plant simplicity); shallow excavation simplifies the mining equipment at the cost of making the plant more mobile.

If dedicated solely to sulfur and associated volatile-element production, the thermal energy required for this plant would be about 0.1 MW-yr per metric ton of sulfur (assuming 100% duty cycle). Significant energy savings might be realized if sulfur production were piggybacked with oxygen production, or if low-energy solvent extraction of sulfur were developed to replace thermal extraction. Clearly, process development with a clear definition of end use is necessary if lunar sulfur is to be taken seriously as a potential resource.

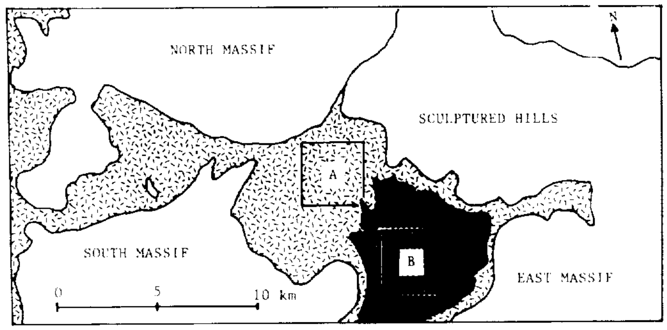


Fig. 3. A simplified version of an albedo map of the Apollo 17 landing site (modified from *Muehlberger et al.*, 1973). Massifs and hills of the nonbasaltic highlands surround an embayment flooded by high-titanium, high-sulfur basalts (light pattern); the eastern part of the embayment includes a terrain of very low albedo (dark pattern), which is attributed by Muehlberger et al. to an extensive pyroclastic mantle. Squares A and B show the dimensions of 10-km^2 × 10-cm-deep patches mined out of the regolith; A would yield ~10^3 MT of sulfur and B would yield ~7×10^2 MT.

Acknowledgments. This study was completed with the support of the National Aeronautics and Space Administration and the U.S. Department of Energy. Reviews by E. Jones, W. Field, E. Cameron, and L. Taylor helped to improve the text and the technical content of the paper.

EPILOGUE

Fire and Brimstone

A mechanical dragon, breathing fire and smoke,
But it lives off of sulfur instead of off coke.
It rolls down the rails of St. Lucifer's line
On a journey to a place that is far from divine.

But the fire and brimstone that makes up our hell
May some day prove useful to mankind as well,
For brimstone-based rockets reaching out into space
Could open the heavens for the human race.

DP 4/88

REFERENCES

Bagotzky V. S. and Skundin A. M. (1980) *Chemical Power Sources.* Academic, New York. 387 pp.

Blacic J. D. (1985) Mechanical properties of lunar materials under anhydrous hard vacuum conditions: Applications of lunar glass structural components. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 487-495. Lunar and Planetary Institute, Houston.

Burow D. F. (1970) Liquid sulfur dioxide. In *The Chemistry of Non-aqueous Solvents, Vol. III* (J. J. Lagowski, ed.), pp. 137-185. Academic, New York.

Butler P. Jr. and Meyer C. Jr. (1976) Sulfur prevails in coatings on glass droplets: Apollo 15 green and brown glasses and Apollo 17 orange and black (devitrified) glasses. *Proc. Lunar Sci. Conf. 7th,* pp. 1561-1581.

Chopra K. L. and Das S. R. (1983) *Thin Film Solar Cells.* Plenum, New York, pp. 349-389 and 391-481.

Cirlin E. H. and Housley R. M. (1979) Scanning auger microprobe and atomic absorption studies of lunar volcanic volatiles. *Proc. Lunar Planet. Sci. Conf. 10th,* pp. 341-354.

Crow L. J. and Bates R. C. (1970) Strengths of sulfur-basalt concretes. *U.S. Dep. Inter., Bur. Mines, RI 7349.* 21 pp.

Cutler A. H. and Krag P. (1985) A carbothermal scheme for lunar oxygen production. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 559-569. Lunar and Planetary Institute, Houston.

Dokiya M., Fukuda K., Kameyama T., and Yokokawa H. (1979) A feasibility study on thermochemical water-splitting cycles using sulfur compounds. In *Hydrogen Energy System, Vol. 2. Proceedings of the Second World Hydrogen Energy Conference.* pp. 499-512. Pergamon, New York.

Flood D. J. (1986) Space solar cell research: Problems and potential. In *SPIE Vol. 706, Photovoltaics for Commercial Solar Power Applications* (D. Adler, ed.), pp. 34-39. Proceedings of SPIE—The International Society for Optical Engineering. SPIE, Bellingham, Washington.

Friedlander H. N. (1985) An analysis of alternate hydrogen sources for lunar manufacture. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 611-618. Lunar and Planetary Institute, Houston.

Gibson E. K. Jr. (1973) Thermal analysis-mass spectrometer computer system and its application to the evolved gas analysis of Green River shale and lunar soil samples. *Thermochim. Acta, 5,* 243-255.

Gibson E. K. Jr. and Moore G. W. (1973) Carbon and sulfur distributions and abundances in lunar fines. *Proc. Lunar Sci. Conf. 4th,* pp. 1577-1586.

Gibson E. K. Jr. and Moore G. W. (1974) Sulfur abundances and distributions in the valley of Taurus-Littrow. *Proc. Lunar Sci. Conf. 5th,* pp. 1823-1837.

Gibson E. K. Jr., Brett R., and Andrawes F. (1977) Sulfur in lunar basalts as a function of bulk composition. *Proc. Lunar Sci. Conf. 8th,* pp. 1417-1428.

Gibson M. A. and Knudsen C. W. (1985) Lunar oxygen production from ilmenite. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 543-550. Lunar and Planetary Institute, Houston.

IAEA (International Atomic Energy Association) (1969) *Radiation Damage and Sulphydryl Compounds.* IAEA Panel Proceedings Series, Vienna. 191 pp.

Kerridge J. F., Kaplan I. R., and Petrowski C. (1975) Evidence for meteoritic sulfur in the lunar regolith. *Proc. Lunar Sci. Conf. 6th,* pp. 2151-2162.

Leclercq R. (1972) Commercially important sulfur compounds. In *Sulfur in Organic and Inorganic Chemistry* (A. Senning, ed.), pp. 207-221. Marcel Drekker, New York.

LSPET (Lunar Sample Preliminary Examination Team) (1972) Preliminary examination of lunar samples. In *Apollo 16 Preliminary Science Report,* pp. 7-1 to 7-58. NASA SP-315, Washington, DC.

MacElroy R. D., Klein H. P., and Averner M. M. (1985) The evolution of CELSS for lunar bases. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 623-633. Lunar and Planetary Institute, Houston.

Meek T. T., Vaniman D. T., Blake R. D., and Cocks F. H. (1987) Electromagnetic energy applied to and gained from lunar materials. In *Symposium '86: The First Lunar Development Symposium* (G. M. Andrus, ed.), pp. S86-40a to S86-40e. Lunar Development Council, Pitman, New Jersey.

Meyer C. Jr., McKay D. S., Anderson D. H., and Butler P. Jr. (1975) The source of sublimates on the Apollo 15 green and Apollo 17 orange glass samples. *Proc. Lunar Sci. Conf. 6th,* pp. 1673-1699.

Muehlberger W. R. et al. (1973) Preliminary geologic investigation of the Apollo 17 landing site. In *Apollo 17 Preliminary Science Report,* pp. 6-1 to 6-91. NASA SP-330, Washington, DC.

National Commission on Space (1986) *Pioneering the Space Frontier.* Bantam, New York. 211 pp.

Pfeiffer J. R., ed. (1975) *Sulfur Removal and Recovery from Industrial Processes.* Advances in Chemistry Series 139, American Chemistry Society, Washington, DC. 221 pp.

Rosenberg S. D. (1985) A lunar-based propulsion system. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 169-176. Lunar and Planetary Institute, Houston.

Rothschild W. G. (1964) γ-ray decomposition of pure liquid sulfur dioxide. *J. Am. Chem. Soc., 86,* 1307-1309.

Russak M. A., Reichman J., Witzke H., Deb S. K., and Chen S. N. (1980) Thin film CdSe photoanodes for electrochemical photovoltaic cells. *J. Electrochem. Soc., 127,* 725-733.

Sulphur Institute (1979) *Sulphur Research and Development 2* (J. S. Platou and R. Pond, eds.). The Sulphur Institute, Washington, DC. 20 pp.

von Sonntag C. (1987) *The Chemical Basis of Radiation Biology.* Taylor and Francis, New York. 515 pp.

Weast R. C., ed. (1982) *Handbook of Chemistry and Physics,* 63rd edition, F-46. CRC, Boca Raton, Florida.

Williams R. J. and Jadwick J. J., eds. (1980) *Handbook of Lunar Materials.* NASA RP-1056. 120 pp.

C-2

AVAILABILITY OF HYDROGEN FOR LUNAR BASE ACTIVITIES

Roberta Bustin

Department of Chemistry
Arkansas College
Batesville AK 72501

Everett K. Gibson Jr.

Mail Code SN2
Planetary Sciences Branch
NASA Johnson Space Center
Houston TX 77058

Hydrogen will be needed on a lunar base to make water for consumables, to provide fuel, and to serve as a reducing agent in the extraction of oxygen from lunar minerals. This study was undertaken in order to learn more about the abundance and distribution of solar-wind-implanted hydrogen. Hydrogen was found in all samples studied, with concentrations varying widely depending on soil maturity, grain size, and mineral composition. Seven cores returned from the Moon were studied. Although hydrogen was implanted in the upper surface layer of the regolith, it was found throughout the cores due to micrometeorite reworking of the soil.

INTRODUCTION

Considering lunar materials from the perspective of utilizing them in space, hydrogen is one of the most valuable lunar resources. It will be needed in lunar base activities in making water, in reducing oxides, and in providing fuel for orbital transfer vehicles.

Solar wind has irradiated the lunar surface for extensive periods of time, implanting hydrogen in the lunar soil (*Becker,* 1980). In order to know if usable quantities of hydrogen are present within the lunar regolith, the abundances, distributions, and locations of hydrogen-containing lunar materials must be fully understood. In this study, bulk soils, size separates, mineral separates, and core samples have been examined.

EXPERIMENTAL TECHNIQUES

Hydrogen was extracted from lunar soil by vacuum pyrolysis (*Carr et al.,* 1987). Weighed lunar samples were placed directly into an alumina tube that was then attached to the sampling line and evacuated to a pressure of 1×10^{-2} atm. Hydrogen was extracted by heating at 900°C for 3 min using a resistance wire furnace. The liberated hydrogen was injected directly into a gas chromatograph (GC) equipped with a 12-ft Molecular Sieve 5A column and a helium ionization detector. The amount of hydrogen was determined from a calibration curve.

HYDROGEN ABUNDANCE

Bulk Surface Soils

Hydrogen abundances were determined for 31 bulk soils, with at least 1 soil from each of the 6 Apollo exploration sites. The results are given in Table 1. Hydrogen concentrations of these bulk surface soils ranged from 3.2 to 60.2 μg/g, with an average value of 36.3 μg/g. Using this "average" bulk surface soil value, 1 ton of lunar soil could provide 369 liters of hydrogen gas at STP.

Earlier studies have shown that concentrations of the noble gases, nitrogen, and carbon increase with increasing soil maturity as measured by the surface exposure index, I_s/FeO (*Charette and Adams,* 1975; *Morris,* 1986; *Morris et al.,* 1989). In general, our results showed that solar wind hydrogen also follows this same trend. Average hydrogen values for all immature, submature, and mature soils were 10.8, 35.3, and 44.6 μg/g, respectively.

Only three of the bulk soils examined had extremely low hydrogen content. The Apollo 16 soil 61221,11, a subsurface soil with abnormally coarse grain size from Plum Crater, had a hydrogen concentration of 3.2 μg/g. This soil contained only 6% agglutinates and had an I_s/FeO value of 9.2 (*Morris et al.,* 1983). The Apollo 12 soil 12033,467, with a hydrogen concentration of 3.2 μg/g, was collected from the bottom of a trench in Head Crater and had 17% agglutinates and an I_s/FeO value of 14.6 (*Morris et al.,* 1983). The Apollo 17 soil 74220, orange soil collected on the rim of Shorty Crater, had a hydrogen concentration of 3.3 μg/g. This is an extremely immature soil, with only 2% agglutinates and an I_s/FeO maturity index of 1 (*Morris et al.,* 1983).

Except for core samples, the bulk soils having the highest concentrations of hydrogen were 75121,6 and 15261,26 with 60.2 and 58.2 μg/g, respectively. Both of these were mature soils with I_s/FeO values of 67 and 77, respectively. Soil 75121,6 had 63% agglutinates, the second highest value of any soil studied to date. Soil 15261,26 was also high in agglutinates with 50.5% (*Morris et al.,* 1983).

This relationship between soil maturity and hydrogen concentration could prove to have practical value as sites are chosen for "mining" hydrogen on the lunar surface.

Grain Size

Because the majority of the hydrogen in lunar soils has been implanted by solar wind, a marked surface correlation would be predicted. Compared to large grains, smaller-sized grains would be expected to show larger hydrogen abundances because of the

TABLE 1. Hydrogen abundances in bulk lunar soils.

Sample Number	Brief Description[1]	Hydrogen Abundance (μg/g) This Study	Literature Values
10084,149	Mature, from fines in Bulk Sample Container	54.2	44.7[2], 45.9[2], 90.0[3]
12033,467	Immature, from a trench in Head Crater	3.2	1.9[4]
12070,127	Submature, from rim of Surveyor Crater	39.2	37.8[4]
14003,71	Mature, collected near the LM	50.8	26.8[5], 29.8[5]
14163,178	Submature, surface sample near the LM	45.6	
15021,2	Mature, surface sample 25 m W of the LM	49.6	62.1[6]
15210,2	Mature, fillet sample from St. George Crater	54.7	
15261,26	Mature, from bottom of a small trench	58.2	
15271,25	Mature, surface soil	47.2	
15301,25	Submature, from Spur Crater	44.6	52.2[7], 50.0[8]
15471,12	Submature, from Dune Crater	35.9	
15601,31	Immature, collected near Hadley Rille	33.6	27.8[9], 36.8[9]
60051,15	Submature, probably ejecta from a small crater	16.0	
60501,1	Mature, surface soil	35.8	
61221,11	Immature, from trench bottom on Plum Crater rim	3.2	7.8[6], 35.0[8]
64421,61	Mature, from trench bottom in subdued crater	36.2	45.6[6]
64801,30	Mature, from crater rim on Stone Mountain	33.0	
66041,12	Mature, from crater rim at Stone Mountain base	35.2	
69941,36	Mature, collected in shadow of small boulder	41.7	34.3[10], 65.0[11]
69961,33	Mature, collected under a small boulder	22.7	49.0[11]
70011,19	Submature, collected under the LM	45.8	47.2[12], 55.1[13]
71501,138	Submature, part of rake sample	34.7	49.6[12]
73141,8	Submature, from 15 cm below the surface	27.0	
74220,20	Immature, orange soil from rim of Shorty Crater	3.3	0.2[6], 0.6[14]
75111,5	Submature, from inner slope of Victory Crater	42.2	
75121,6	Mature, between Victory and Horatio Craters	60.2	
76240,9	Submature, shadowed from overhang of a boulder	38.4	
76260,3	Submature, "skim" sample	32.9	
76280,6	Submature, "scoop" sample below sample 76260	28.0	
76501,18	Submature, surface sample	43.8	43.0[12]
78501,20	Submature, surface sample near rim of crater	29.0	32.8[9]

References: [1]*Morris et al.* (1983); [2]*Epstein and Taylor* (1970); [3]*Friedman et al.* (1970); [4]*Epstein and Taylor* (1971); [5]*Merlivat et al.* (1972); [6]*Epstein and Taylor* (1973); [7]*Epstein and Taylor* (1972); [8]*Des Marais et al.* (1974); [9]*Merlivat et al.* (1974); [10]*Becker* (1980); [11]*Stoenner et al.* (1974); [12]*Petrowski et al.* (1974); [13]*Epstein and Taylor* (1975); [14]*Chang et al.* (1974).

increase in the ratio of surface area to mass. *Eberhardt et al.* (1972) found such a correlation for the solar wind noble gases and showed that the grain size dependence of these gases can be described by the relationship $C \propto d^{-n}$ where C is the gas concentration in a grain size fraction with average diameter d, and -n is the slope in a log concentration vs. log grain size plot. Several studies with noble gases have shown that not only is a surface-correlated component present, but that a volume-correlated, grain-size-independent component is also evident (*Bogard,* 1977; *Eberhardt et al.,* 1972; *Etique et al.,* 1978; *Morris,* 1977; *Schultz et al.,* 1977). The present study indicates a similar relationship between hydrogen abundance and grain size for the six lunar samples studied, as shown in Fig. 1. When log hydrogen abundance is plotted against log grain size, a linear relationship is seen for small grain sizes. Thus, solar wind implantation of hydrogen is definitely a surface phenomenon. However, as constructional particles such as agglutinates are built up from much smaller grains, and surfaces that were originally exposed become buried inside the particles, gases that were implanted on surfaces become trapped inside, and a volume-correlated component becomes evident for these large grains. This is shown graphically by a flattening of the curve for large grain sizes.

The soil that showed the least amount of volume correlation for large grain sizes was sample 71501,138, the most immature of all those used in the grain size study. This result predicts that this soil has not seen much micrometeorite reworking and, thus, is not rich in agglutinates and other constructional particles that would have trapped hydrogen during formation. This is verified by a soil composition study (*Morris et al.,* 1983) that showed only 35% agglutinates in this soil.

Table 2 gives the hydrogen concentrations for each particle size for five lunar soils and a breccia. For each sample, the $<20\mu m$ grain size fraction was enriched by approximately a factor of 3 over the value obtained experimentally for the bulk soil. Also, a majority (from 59.4% to 87.4%) of the total hydrogen in each sample was found in the smallest grain size. Mass balance calculations served as a check for the experimentally determined values. As shown in Table 2, there was good agreement between the calculated and the experimentally determined values of hydrogen concentration.

The technology required to separate the fine grains from bulk soil is simple, making it feasible to include such a separation prior to extracting the hydrogen. If this could be done, approximately 1100 liters of hydrogen at STP (based on the average bulk soil

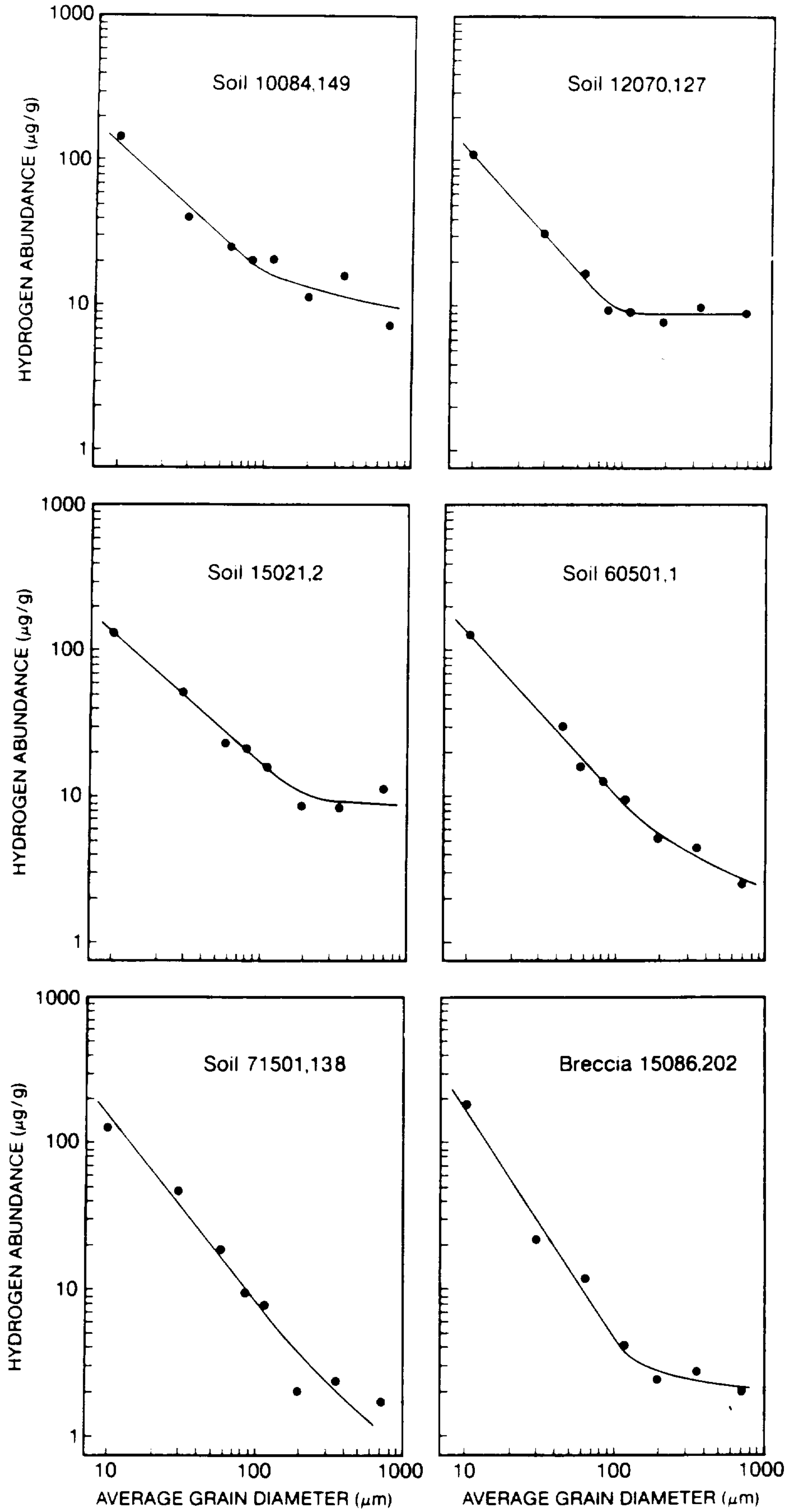


Fig. 1. Hydrogen abundances in grain size fractions of five bulk soil samples and one regolith breccia.

TABLE 2. Hydrogen abundances of grain size fractions and mass balance calculations.

Sample Number	Grain Size (μm)	Weight Percent	Hydrogen Content (μg/g)	Contribution to Bulk (μg/g)	Hydrogen Calculated (μg/g)	Found (μg/g)
10084,149	<20	25.78	146.7	37.8		
	20-45	18.33	39.7	7.3		
	45-75	15.01	24.4	3.7		
	75-90	5.01	20.1	1.0		
	90-150	12.24	20.2	2.5		
	150-250	9.06	11.3	1.0		
	250-500	8.73	15.7	1.4		
	500-1000	5.82	7.2	0.4	55.1	54.2
12070,127	<20	22.35	107.4	24.0		
	20-45	17.34	30.1	5.2		
	45-75	14.82	16.2	2.4		
	75-90	5.09	9.0	0.5		
	90-150	13.37	8.7	1.2		
	150-250	10.60	7.5	0.8		
	250-500	8.80	9.4	0.8		
	500-1000	7.63	8.5	0.6	35.5	39.2
15021,2	<20	23.02	128.5	29.6		
	20-45	22.96	51.1	11.7		
	45-75	15.61	22.4	3.5		
	75-90	4.37	20.8	1.1		
	90-150	13.26	15.5	2.1		
	150-250	9.25	8.4	0.8		
	250-500	7.23	8.2	0.6		
	500-1000	3.31	11.0	0.4	49.8	49.6
60501,1	<20	24.12	124.1	29.9		
	20-45	17.76	43.0	7.6		
	45-75	13.48	16.1	2.2		
	75-90	4.40	12.8	0.6		
	90-150	11.54	9.6	1.1		
	150-250	9.72	5.2	0.5		
	250-500	10.75	4.4	0.5		
	500-1000	8.22	2.6	0.2	42.6	35.8
71501,138	<20	17.62	126.4	22.3		
	20-45	17.67	47.2	8.3		
	45-75	15.60	18.5	2.9		
	75-90	4.42	9.4	0.5		
	90-150	14.75	7.7	1.1		
	150-250	11.51	2.0	0.2		
	250-500	10.69	2.4	0.3		
	500-1000	6.64	1.7	0.1	35.7	34.7
Breccia	<20	28.62	176.3	50.5		
15086,202	20-45	19.05	21.9	4.2		
	45-90	18.30	11.7	2.1		
	90-150	12.55	4.0	0.5		
	150-250	9.12	2.3	0.2		
	250-500	7.51	2.7	0.2		
	500-1000	4.85	1.9	0.1	57.8	60.4

value) could be obtained for each ton of soil going through the extraction facility. If this size separation were carried out on the most mature soil studied, this value would be increased to approximately 1840 liters at STP.

Soil Components

Signer et al. (1977) looked at the retentivity of solar wind noble gases by several particle types. They found that agglutinates consistently contained the highest noble gas concentrations among soil constituents. This is not surprising because agglutinates are constructional particles, built up by micrometeorite impact on the lunar surface. *DesMarais et al.* (1974) studied the distribution of hydrogen with respect to soil particle types. As expected, they found a considerable enrichment of hydrogen in the agglutinate fraction over that in the bulk soil; in fact, agglutinates contained the most hydrogen of any particle type studied. We found a similar enrichment in all but 1 of the 10 hand-picked agglutinate size separates run in this study (Table 3).

Signer et al. (1977) noted high noble gas concentrations in breccia samples. They attributed this to the trapped gases in the particles that make up the breccia. Our results (Table 4) showed a similar hydrogen enrichment in breccias over that found in bulk surface soils.

TABLE 3. Hydrogen abundances of agglutinates compared to original samples.

Sample Number	Grain Size (μm)	Original Sample (μg/g)	Agglutinate Fraction (μg/g)
10084,149	150-250	11.3	16.6
	250-500	15.7	16.8
	500-1000	7.2	11.5
12070,127	250-500	9.4	7.4
15021,2	250-500	8.2	11.2
60501,1	250-500	4.4	11.4
71501,138	90-150	7.7	22.2
	150-250	2.0	20.0
	250-500	2.3	10.2
	500-1000	1.7	4.7

TABLE 4. Hydrogen abundances in lunar breccias.

Sample Number	Brief Description*	Hydrogen Abundance (μg/g)
10018,54	Dark gray, fine-grained breccia, returned in the Documented Sample Container	116.6
10021,73	Medium light gray breccia, returned in the Contingency Sample Bag	105.2
10048,25	Medium light gray, fine-grained breccia, returned in the Bulk Sample Container	93.3
10056,69	Medium dark gray, microbreccia, returned in the Bulk Sample Container	17.8
10059,38	Medium dark gray, microbreccia, returned in the Bulk Sample Container	96.6
10065,136	Medium dark gray, microbreccia, a grab sample in the Documented Sample Container	95.6
12073,253	Coherent, medium gray breccia, part of the contingency sample, from NW of the LM	21.6
15086,97	Medium gray, friable breccia, collected about 65 m E of the Elbow Crater rim crest	60.4
70175,16	Moderately coherent, highly fractured brown-black breccia, collected near Apollo 17 deep drill core	11.4
70295,23	Medium gray regolith breccia collected at the LM station	77.2
79035,76	Moderately friable breccia locally cemented by glass, from a few meters E of rim crest of Van Serg	44.8
79115,22	Friable, medium gray soil breccia, foliated appearance due to intense fracturing	102.4
79135,33	Polymict matrix fine breccia, collected a few meters SE of Van Serg Crater	92.8
79195,7	Friable, dark gray breccia	19.2

*References: *Butler* (1973); *Fruland* (1983); *Kramer et al.* (1977).

It is well known that ilmenite grains retain helium readily. *Eberhardt et al.* (1972) noted that the ilmenite grain size fractions from soil 12001 were considerably enriched in helium (up to 12 times) over the corresponding bulk grain size fractions. *Hintenberger et al.* (1971) found that the ilmenite grains in some lunar soils were enriched in helium by a factor of 3 to 6 over the bulk material in the same grain size range. Because hydrogen is also a solar wind species, it is felt that the retention mechanism would be similar for hydrogen and helium and that ilmenite would also be high in hydrogen. No ilmenite grains were available for this study; however, some interesting observations may be made. Apollo 16 soils are highland soils and are known to be lower in

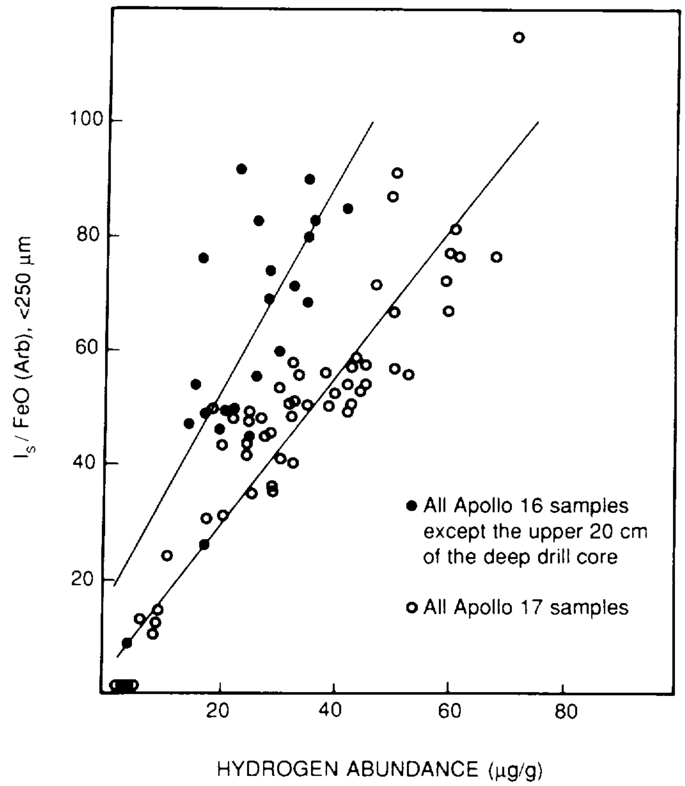


Fig. 2. Comparison of hydrogen retentivity of Apollo 16 and Apollo 17 soils. The slope of the Apollo 16 line is 1.82, compared to 1.28 for the Apollo 17 line. Maturity data as measured by the I_s/FeO index are from *Gose and Morris* (1977); *Morris* (1986), *Morris et al.* (1978, 1979, 1983).

TABLE 5. Hydrogen abundances in lunar basalts.

Sample Number	Brief Description*	Hydrogen Abundance (μg/g)
15016,41	Medium-grained, vesicular olivine-normative, collected 30 m from the ALSEP central station	2.2
15058,72	Coarse-grained, vuggy quartz normative collected on E flank of Elbow Crater	1.8
15065,39	Coarse-grained, quartz normative with pigeonite phenocrysts, collected on E flank of Elbow Crater	1.2
15076,8	Tough, coarse-grained with some pigeonite phenocrysts, collected on E flank of Elbow Crater	1.4
15085,97	Coarse-grained quartz-normative mare basalt, collected on E flank of Elbow Crater	1.8
15499,20	Vitrophyric pigeonite basalt, collected on the S rim of Dune Crater	2.0
15555,136	From "Great Scott," a medium-grained olivine basalt, collected 12 m N of rim of Hadley Rille	1.7
15556,159	Medium-grained, extremely vesicular olivine-normative, collected 60 m NE of rim of Hadley Rille	1.8
70035,1	Moderate brown basalt	2.2
70215,54	Fine-grained, medium dark gray with brownish tint	2.4
74275,56	Medium dark gray porphyritic basalt	3.8
75035,37	Medium to brownish gray	1.8
75055,6	White and medium brownish gray	3.5
78505,26	Coarse, vuggy, medium dark brownish gray	2.4

*References: *Butler* (1973); *Ryder* (1985).

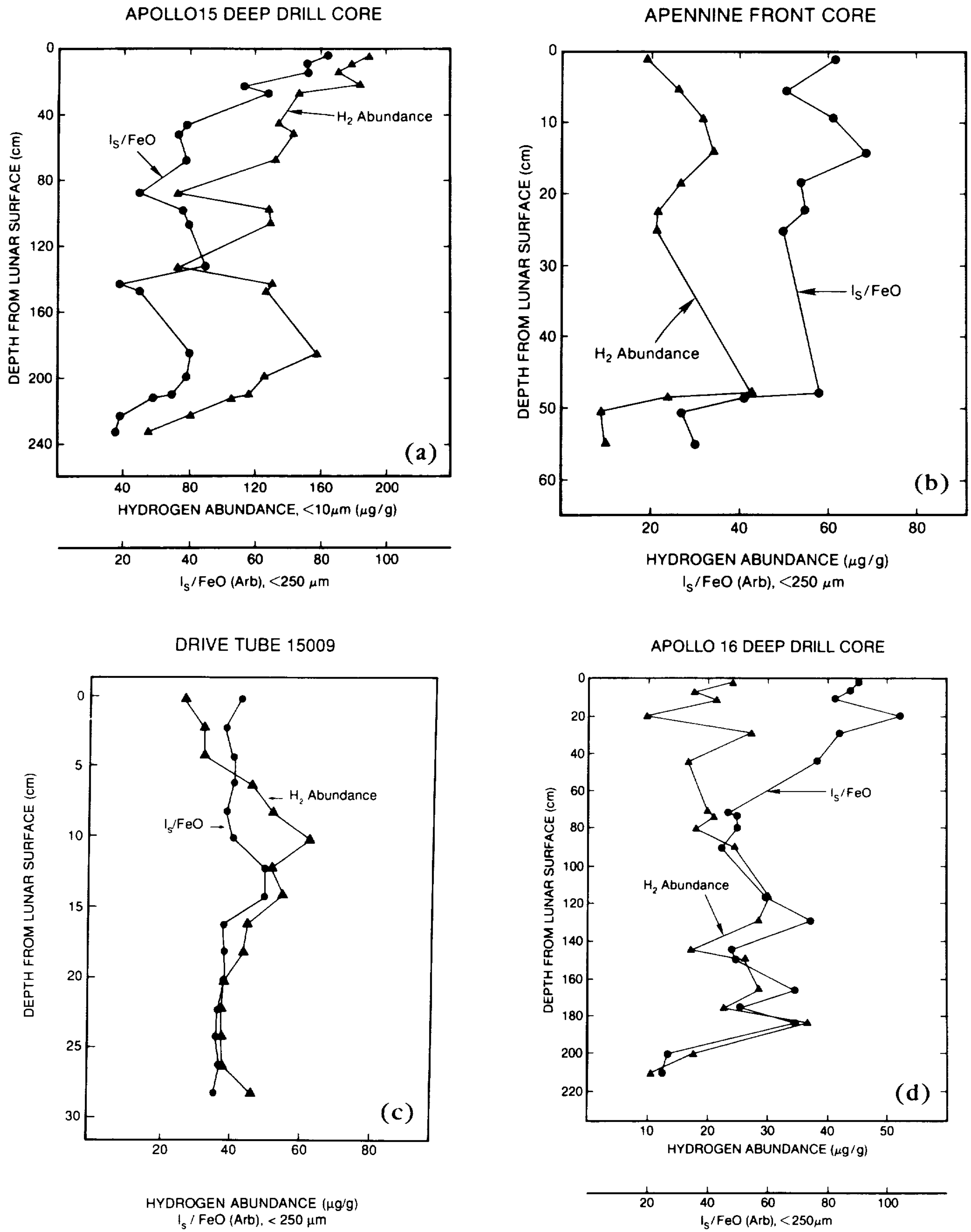
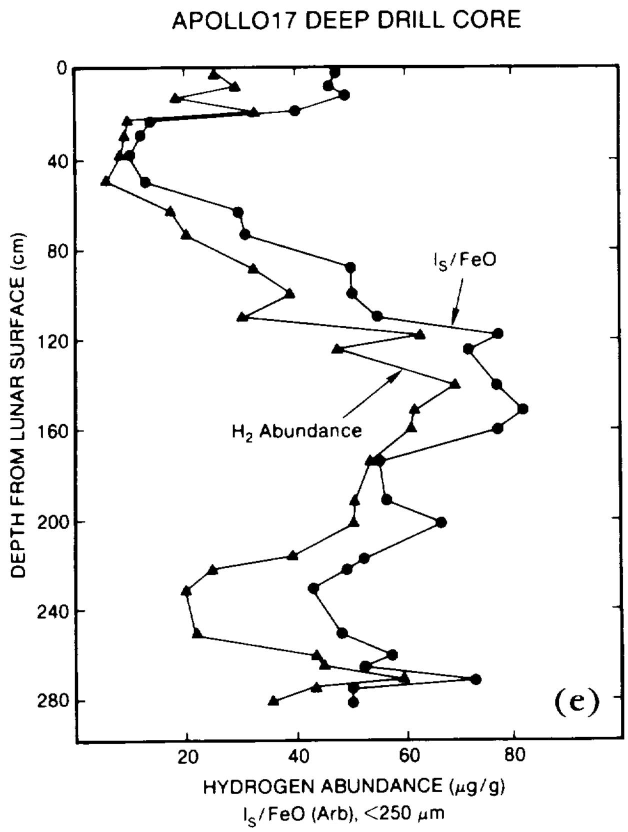
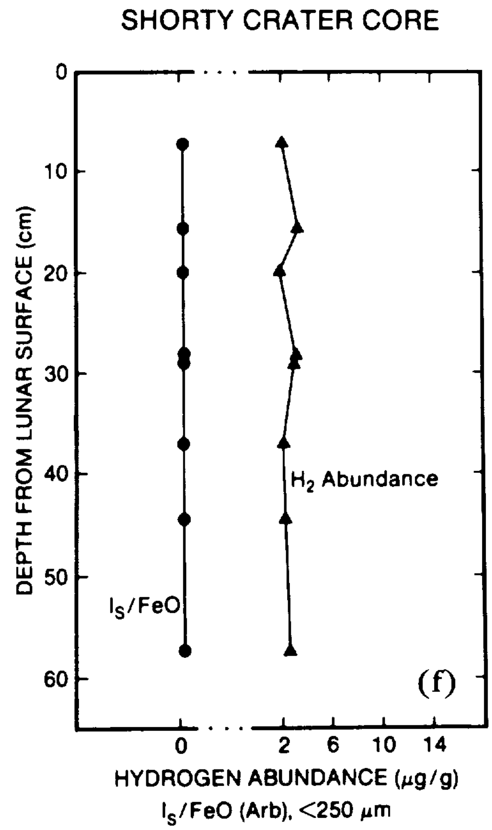
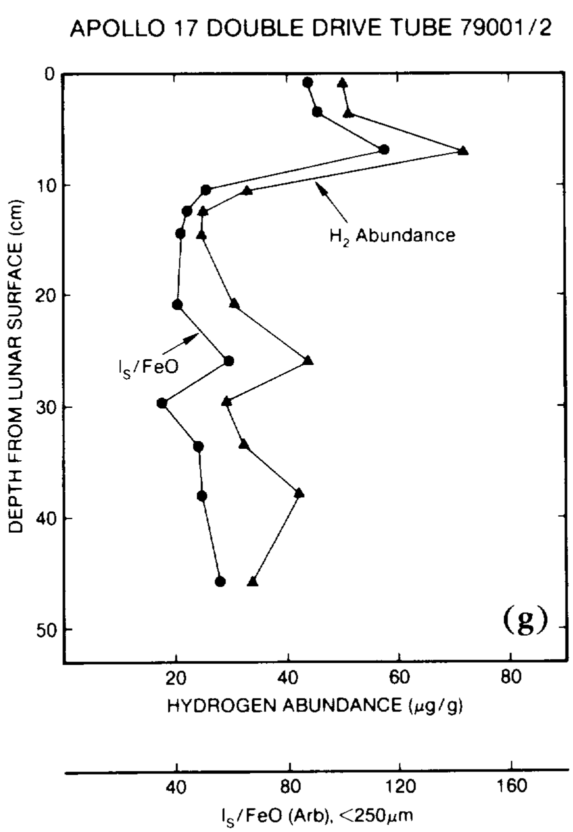


Fig. 3. Depth profiles of I_s/FeO and hydrogen abundance for seven core tubes. Maturity data as measured by the I_s/FeO index are from *Bogard et al.* (1982); *Gose and Morris* (1977); *Heiken et al.* (1976); *Morris et al.* (1978, 1979); *Morris* (1986); *Schwarz* (1988); R. V. Morris, personal communication (1987).







ilmenite that mare soils (*Taylor*, 1975). Hydrogen concentrations in highland soils were noticeably lower than would have been predicted from maturity data. The average hydrogen concentration in the eight Apollo 16 bulk surface soils studied was only 28.0 μg/g, compared to 39.2 μg/g for the other 23 bulk surface soils. Although six of the Apollo 16 bulk surface soils were classified as mature according to their I_s/FeO values, their average was only 34.1 μg/g, considerably lower than the average of 53.6 μg/g for all other mature surface soils. In a plot of I_s/FeO vs. hydrogen concentration (Fig. 2), the difference in hydrogen retentivity of the Apollo 16 highland soils and the Apollo 17 mare soils is quite apparent.

DesMarais et al. (1974) studied two very different lunar basalts, sample 15058,73, a porphyritic basalt with very few vugs or cavities, and sample 15556,56, a vesicular basalt. Both of these were low in hydrogen. We studied 14 lunar basalt samples. As Table 5 shows, all these samples had extremely low hydrogen concentrations, ranging only from 1.2 to 3.8 μg/g.

Core Samples

The depositional and irradiational histories of the lunar regolith are reflected in the soil samples from lunar cores. They provide useful information about earlier processes that have occurred on the lunar surface. Hydrogen data on the core samples provide a different kind of valuable information. First, the correlation between hydrogen abundance and soil maturity can often be seen more clearly from core data than from bulk soil data. As shown

in Fig. 3, this correlation is quite striking for several of the cores. Also, from a practical standpoint, if hydrogen is to be mined from the lunar surface, it is essential to have some idea about depth distribution.

Two of the cores were particularly unusual. The Shorty Crater core is relatively homogeneous and consists almost entirely of orange and black glassy droplets. Of all lunar samples studied, the 74001/2 soil below 4.5 cm is believed to have seen the least amount of surface exposure (*Morris et al.,* 1978). The values obtained for hydrogen concentrations throughout the length of the core were extremely low and showed very little variation. These values were very close to the hydrogen concentration found in the local surface soil 74220,20. On the other extreme was the Apollo 17 double drive tube 79001/2. The striking physical feature of this core was a distinct dark-light boundary inclined 25° to 30° from approximately 8.5 to 11 cm below the surface (*Schwarz,* 1986). There is a definite change in both soil maturity and hydrogen abundance at approximately the interface between the dark and light layers. The upper dark section of this core includes the most mature lunar soils ever observed (*Korotev et al.,* 1987). Soils from this section also have the highest hydrogen concentrations of any soils studied. The highest hydrogen value obtained in this study for a bulk soil was 72.0 μg/g, obtained for the 6.5- to 7.0-cm section of this core; this sample also had the highest I_s/FeO value recorded for a bulk soil (*Korotev et al.,* 1987). Grain size separates were run on selected samples from this core. The highest hydrogen values obtained for any samples in the entire study were obtained for the <20-μm grain sizes for the soils in the upper 10 cm of the core. These values were all greater than 269 μg/g, with a high of 306.4 μg/g.

The deepest soil column (~295 cm) returned from the Moon was the Apollo 17 deep drill core. Although we don't know how deep hydrogen extends in the lunar regolith, it is encouraging to see that it is present completely to the bottom of this deep drill core. This makes mining for hydrogen much more feasible than if it were only present in a thin surface layer.

CONCLUSION

Based on these preliminary studies, extraction of solar wind hydrogen from lunar soil appears feasible, particularly if some kind of grain size separation is possible. Even if concentrations are determined to be too low to extract enough hydrogen to use for propulsion, water obtained from the hydrogen could be used for crew activities and industrial processes. When plans for an extraction facility are being made, consideration should be given to the fact that hydrogen concentrations vary significantly from one site to another. A site should be chosen where the soil is mature.

Acknowledgments. The authors gratefully acknowledge the skillful help of S. Wentworth in preparing the grain size separates, of A. Skaugset in handpicking the agglutinates, and of P. Mannion and A. Skaugset in performing some of the hydrogen determinations.

REFERENCES

Becker R. H. (1980) Light elements in lunar soils revisited: Carbon, nitrogen, hydrogen and helium. *Proc. Lunar Planet. Sci. Conf. 11th,* pp. 1743-1761.

Bogard D. D., Morris R. V., Johnson P., and Lauer H. V. Jr. (1982) The Apennine Front core 15007/8: Irradiational and depositional history. *Proc. Lunar Planet. Sci. Conf. 13th,* in *J. Geophys. Res., 87,* A221-A231.

Butler P. Jr. (1973) *Lunar Sample Information Catalog, Apollo 17.* MSC 03211, NASA Johnson Space Center. 447 pp.

Carr R. H., Bustin R., and Gibson E. K. Jr. (1987) A pyrolysis/gas chromatographic method for the determination of hydrogen in solid samples. *Anal. Chim. Acta, 202,* 251-256.

Chang S., Lennon K., and Gibson E. K. Jr. (1974) Abundances of C, N, H, He, and S in Apollo 17 soils from stations 3 and 4: Implications for solar and regolith evolution. *Proc. Lunar Sci. Conf. 5th,* pp. 1785-1800.

Charette M. P. and Adams J. B. (1975) Agglutinates as indicators of lunar soil maturity: The rare gas evidence at Apollo 16. *Proc. Lunar Sci. Conf. 6th,* pp. 2281-2289.

DesMarais D. J., Hayes J. M., and Meinschein W. G. (1974) The distribution in lunar soil of hydrogen released by pyrolysis. *Proc. Lunar Sci. Conf. 5th,* pp. 1811-1822.

Eberhardt P., Geiss J., Graf H., Grogler H., Mendia M. D., Morgeli M., Schwaller H., Stettler A., Krahenbuhl U., and Von Guntens H. R. (1972) Trapped solar wind noble gases in Apollo 12 lunar fines 12001 and Apollo 11 breccia 10046. *Proc. Lunar Sci. Conf. 3rd,* pp. 1821-1856.

Epstein S. and Taylor H. P. Jr. (1970) Stable isotopes, rare gases, solar wind, and spallation products. *Science, 167,* pp. 533-535.

Epstein S. and Taylor H. P. Jr. (1971) O^{18}/O^{16}, Si^{30}/Si^{28}, D/H, and C^{13}/C^{12} ratios in lunar samples. *Proc. Lunar Sci. Conf. 2nd,* pp. 1421-1441.

Epstein S. and Taylor H. P. Jr. (1972) O^{18}/O^{16}, Si^{30}/Si^{28}, C^{13}/C^{12}, and D/H studies of Apollo 14 and 15 samples. *Proc. Lunar Sci. Conf. 3rd,* pp. 1429-1454.

Epstein S. and Taylor H. P. Jr. (1973) The isotopic composition and concentration of water, hydrogen, and carbon in some Apollo 15 and 16 soils and in the Apollo 17 orange soil. *Proc. Lunar Sci. Conf. 4th,* pp. 1559-1575.

Epstein S. and Taylor H. P. Jr. (1975) Investigation of the carbon, hydrogen, oxygen, and silicon isotope and concentration relationships on the grain surfaces of a variety of lunar soils and in some Apollo 15 and 16 core samples. *Proc. Lunar Sci. Conf. 6th,* pp. 1771-1798.

Etique P., Derksen U., Funk H., Horn P., Signer P., and Wieler R. (1978) Helium, neon, and argon in 61501 agglutinates: Implications to gas studies on complex samples. *Proc. Lunar Planet Sci. Conf. 9th,* pp. 2233-2267.

Friedman I., Gleason J. D., and Hardcastle K. G. (1970) Water, hydrogen, deuterium, carbon and C^{13} content of selected lunar material. *Proc. Apollo 11 Lunar Sci. Conf.,* pp. 1103-1109.

Fruland R. M. (1981) *Introduction to the Core Samples from the Apollo 16 Landing Site, 17659.* NASA Johnson Space Center. 45 pp.

Gose W. A. and Morris R. V. (1977) Depositional history of the Apollo 16 deep drill core. *Proc. Lunar Sci. Conf. 8th,* pp. 2909-2928.

Heiken G. H., Morris R. V., McKay D. S., and Fruland R. M. (1976) Petrographic and ferromagnetic resonance studies of the Apollo 15 deep drill core. *Proc. Lunar Sci. Conf. 7th,* pp. 93-111.

Hintenberger H., Weber H. W., and Takaoka N. (1971) Concentrations and isotopic abundances of the rare gases in lunar matter. *Proc. Lunar Sci. Conf. 2nd,* pp. 1607-1625.

Korotev R. L., Morris, R. V., and Lauer H. V. Jr. (1987) Composition and maturity of the Van Serg crater core (section 79002) (abstract). In *Lunar and Planetary Science XVIII,* pp. 509-510. Lunar and Planetary Institute, Houston.

Kramer F. E., Twedell D. B., and Walton W. J. A. Jr. (1977) *Apollo 11 Lunar Sample Information Catalogue (revised).* NASA SP 12522. 471 pp.

Merlivat L., Nief G., and Roth E. (1972) Deuterium content of lunar material. *Proc. Lunar Sci. Conf. 3rd,* pp. 1473-1477.

Merlivat L., Lelu M., Nief G., and Roth E. (1974) Deuterium, hydrogen, and water content of lunar material. *Proc. Lunar Sci. Conf. 5th,* pp. 1885-1895.

Morris R. V. (1977) Origin and evolution of the grain-size dependence of the concentration of fine-grained metal in lunar soils: The maturation of lunar soils to a steady-state stage. *Proc. Lunar Sci. Conf. 8th,* pp. 3719-3747.

Morris R. V. (1986) Report on the FeO and I_s/FeO profiles for lunar core 79002. *Lunar News, 47,* 4.

Morris R. V., Gose W. A., and Lauer H. V. Jr. (1978) Depositional and surface exposure history of the Shorty Crater core 74001/2: FMR and magnetic studies. *Proc. Lunar Planet. Sci. Conf. 9th*, pp. 2033–2048.

Morris R. V., Lauer H. V. Jr., and Gose W. A. (1979) Characterization and depositional and evolutionary history of the Apollo 17 deep drill core. *Proc. Lunar Planet. Sci. Conf. 10th*, pp. 1141–1157.

Morris R. V., Score R., Dardano C., and Heiken G. (1983) *Handbook of Lunar Soils*. NASA Johnson Space Center. 914 pp.

Morris R. V., Korotev R. L., and Lauer H. V. Jr. (1989) Maturity and geochemistry of the Van Serg core (79001/2) with implications for micrometeorite composition. *Proc. Lunar Planet. Sci. Conf. 19th*, pp. 269–284.

Petrowski C., Kerridge J. F., and Kaplan I. R. (1974) Light element geochemistry of the Apollo 17 site. *Proc. Lunar Sci. Conf. 5th*, pp. 1939–1948.

Ryder G. (1985) *Catalog of Apollo 15 Rocks*. NASA Johnson Space Center. 1295 pp.

Schultz L., Weber H. W., Spettel B., Hintenberger H., and Wänke H. (1977) Noble gas and element distribution in agglutinate and bulk grain size fractions of soil 15601. *Proc. Lunar Sci. Conf. 8th*, pp. 2799–2815.

Schwarz C. (1986) Newly-opened Apollo 17 core reveals dark/light contact. *Lunar News, 47*, 5–7.

Schwarz C. (1988) Dissection of lunar core 15009 completed. *Lunar News, 51*, 5–9.

Signer P., Baur H., Derksen U., Etique P., Funk H., Horn P., and Wieler R. (1977) Helium, neon, and argon records of lunar soil evolution. *Proc. Lunar Sci. Conf. 8th*, pp. 3657–3683.

Stoenner R. W., Davis R. Jr., Norton E., and Bauer M. (1974) Radioactive rare gases, tritium, hydrogen, and helium in the sample return container, and in the Apollo 16 and 17 drill stems. *Proc. Lunar Sci. Conf. 5th*, pp. 2211–2229.

Taylor S. R. (1975) *Lunar Science: A Post-Apollo View*. Pergamon, New York. 372 pp.

THE INFLUENCE OF LUNAR PROPELLANT PRODUCTION ON THE COST-EFFECTIVENESS OF CISLUNAR TRANSPORTATION SYSTEMS

H. H. Koelle

Aerospace Institute
Technical University of Berlin
Berlin, Germany

It is well known that propellants produced at the points of destination such as the Moon or Mars will help the economy of space transportation, particularly if round trips with a crew are involved. The construction and operation of a lunar base shortly after the turn of the century is one of the space programs under serious consideration at the present time. Space transportation is one of the major cost drivers. With present technology, if expendable launchers were employed, the specific transportation costs of one-way cargo flights would be approximately $10,000/kg (1985) at life-cycle cumulative 100,000 ton payload to the lunar surface. A fully reusable space transportation system using lunar oxygen and Earth-produced liquid hydrogen (LH_2) would reduce the specific transportation costs by one order of magnitude to less than $1000/kg at the same payload volume. Another case of primary interest is the delivery of construction material and consumables from the lunar surface to the assembly site of space solar power plants in geostationary orbit (GEO). If such a system were technically and economically feasible, a cumulative payload of about 1 million tons or more would be required. At this level a space freighter system could deliver this material from Earth for about $300/kg (1985) to GEO. A lunar space transportation system using lunar oxygen and a fuel mixture of 50% Al and 50% LH_2 (that has to come from Earth) could reduce the specific transportation costs to less than half, approximately $150/kg. If only lunar oxygen were available, these costs would come down to $200/kg. This analysis indicates a sizable reduction of the transportation burden on this type of mission. It should not be overlooked, however, that there are several uncertainties in such calculations. It is quite difficult at this point to calculate the cost of lunar-produced O and/or Al. This will be a function of production rate and life-cycle length. In quoting any cost of this nature, it is very important to state the cumulative transportation volume, since this is a very sensitive parameter. Nevertheless, cost models must be developed now to understand fully the interdependencies of a large number of parameters and to provide the best possible data for planning purposes. Without such data, mission modes and vehicle designs or sizes cannot be selected intelligently.

INTRODUCTION

The importance of extraterrestrial production of propellants for the evolution of space flight was recognized rather early (*Stehling,* 1958; *Cole and Segal,* 1964; *Bock,* 1979); but only now does planning for a return to the Moon (*Paine et al.,* 1986; *Ride,* 1987; *Koelle et al.,* 1987) make this proposition an objective that may become reality in the forseeable future.

The Apollo lunar landing program did not include the possibility of using lunar-produced propellants because it was a short-term exploratory mission on a tight schedule with cost being a secondary parameter. Returning to the Moon early next century makes sense only if the goal is to construct and operate a permanent lunar base there that will evolve into a lunar settlement in due course. This will be possible if cost is the primary concern. A permanent lunar base must be affordable!

The acquisition of a lunar base and its operations should therefore be based on using lunar resources to the largest possible extent. Areas where this can be done are production of construction materials from lunar feedstock, using a closed life-support system, and production of lunar propellants employing solar energy. This will necessarily have to be an evolutionary process toward self-sufficiency. The beginning will be modest in nature. Such a process can be analyzed best by a systems simulation. The first results of such studies have shown that progress will not be easy (*Koelle and Johenning,* 1982, 1986; *Fairchild and Roberts,;* *1986*).

Among other things, it has become clear that chemical propulsion systems using liquid hydrogen (LH_2) and liquid oxygen (LOX) are hard to beat if lunar propellants become available (*Thomas,* 1984). Even in this case, the largest contribution to the high cost of space transportation in cislunar space is the need to import the fuel (LH_2) from Earth. This accounts for up to 80% of the specific transportation cost in terms of $/kg (*Koelle and Johenning,* 1986). Thus, we should try to find lunar-produced fuels to mix with terrestrial hydrogen without losing too much performance (exhaust velocity). Lunar-produced hydrogen would be ideal, but at present it is uncertain whether this will be ecomically feasible. Another way to reduce the amount of terrestrial hydrogen is to replace some of it by aluminum powder produced on the Moon. This has been analyzed previously and has shown promise (*Bock,* 1979). Recently, R. L. Zurawski has shown that the addition of aluminum to hydrogen will reduce the specific impulse of this mixture only moderately if the aluminum share is held to about 50% by mass. At a mixture ratio of 6:1 (LOX:fuel) the loss is in the order of

17-18%. Using these results, it is now of interest to calculate the potential for cost reduction in a scenario of lunar base development with lunar fuel production.

The primary assumptions made in this analysis are as follows: (1) A space freighter will be available for the mission leg from the Earth's surface to low Earth orbit (LEO) in a two-stage version or to geostationary orbit (GEO) or alternatively to lunar orbit (LUO) in a three-stage version. The payload capacity to LEO is 360 MT, to GEO and LUO 92 MT. The third stage can also be used as a space ferry between LEO and LUO with refueling at either end (*Koelle and Johenning,* 1986). This cargo ferry has an SSME derived propulsion system with an extended nozzle delivering an I_{sp} of 4600 m/sec. (2) A propellant depot will be stationed in a low LUO to store propellants delivered from the Earth or the Moon. This space operation center can be used for refueling, payload transfer, maintenance, and repair work at a fee. (3) The space ferry and the lunar bus (for transportation between low LUO and the lunar surface) will have a hardware compatibility near 90% of the third stage of the launch vehicle. (4) The main emphasis of this analysis is on cargo transportation; passenger vehicles will probably be smaller in size and depart from LEO to maximize crew safety. It will also use a multiengine vehicle configuration for the same reason. However, passenger flights require propellants for the return flight to Earth that may amount to 50% of the lunar transportation capacity. This will certainly affect the specific transportation cost to LEO and has to be taken into consideration when calculating overall transportation costs.

CASE STUDIES

Several modes of transportation in cislunar space are of interest with respect to the cost-effectiveness of utilizing lunar propellants to obtain an overall picture, specifically: (1) supply of a lunar base with terrestrial products without using lunar propellants; (2) supply of a lunar base with terrestrial products utilizing lunar-produced propellants; (3) supply of an SSPS construction site in GEO with terrestrial materials only; and (4) supply of an SSPS construction site in GEO using terrestrial and lunar sources.

Previous analyses have shown that the following parameters are of primary importance: (1) annual transport volume (MT/year); (2) system life cycle (years); (3) specific transportation cost between Earth's surface and LUO and the lunar surface, respectively ($/kg); (4) production cost of lunar propellants ($/kg); (5) space vehicle hardware depreciation ($/flight); (6) flight operations cost without propellants ($/flight); (7) mixture ratio of lunar propellants to Earth propellants; (8) vehicle payload capability (kg/flight); (9) vehicle state-of-the-art in terms of propellant fraction; (10) RDT&T burden to be shared by this program; (11) vehicle turnaround time between flights (flights/year); and (12) average constructive lifetime (years or flights/vehicle).

The life-cycle cost (LC) of a space transportation system operating as a cargo carrier from the lunar surface (LS) to GEO is comprised of the following elements: C_D (development cost), C_H (vehicle hardware cost), C_P (vehicle propellant cost), and C_L (launch operation costs other than propellants).

The size of the program is determined by the life-cycle cumulative volume of the destination payload. If this is a large space program on the order of 1×10^6 MT or more, the development costs are less than 5% and can be neglected in an analysis of the cost-effectiveness of large-scale lunar propellant production.

If the number of reuses is larger than 100 and the hardware masses of the vehicles to be compared are nearly identical, then the per-flight vehicle hardware costs will be almost the same. Launch operations costs are the costs involved to prepare the space vehicle on the lunar surface, refuel it in LUO, execute a payload transfer (if required), and unload the payload at the destination. These operations will also include maintenance and repair work at these places. These costs should be proportional to the number of flights in first approximation. The difference of vehicle alternatives will appear primarily in the cost of propellants. The cost of lunar propellants produced in quantity should be on the order of $3-10/kg, but the propellants imported from Earth may be on the order of $300-1000/kg, depending on program size.

ONE-WAY CARGO MISSION MODES

One class of missions can be defined as flights with cargo only to be transported from the Earth's surface to the lunar surface in support of lunar base operations. They are relatively clear-cut with respect to velocity requirements and the state-of-the-art. The effectiveness of these missions depends primarily on the cost-effectiveness of the launch vehicles and on the degree of reusability, but not so much on the use of lunar propellants. They are useful, however, as a point of departure and to compare other mission modes in cislunar space.

It is well known that the cost-effectiveness of space transportation systems is heavily dependent on the life-cycle cumulative payload volume that will determine the launch rates. These in turn determine the launch cost. Thus, we will investigate the range of 10^5 MT to 10^6 MT of cumulative payload delivered during the system life to the lunar surface. Using a 50-year life cycle, not inappropriate for a lunar base, this translates into 2000 to 20,000 MT per annum or, if delivered in 100 MT units, equivalent to 20 to 200 flights per year. This is not an unreasonable assumption for the annual average of the first half of the next century.

The mission modes investigated here are as follows: (1) For reference, an updated Saturn V vehicle (using SSME in the upper stages called Saturn VI) will be used on an expendable base with direct flights to the lunar surface in a three-stage configuration. The upper and lower limits for the effectiveness are obtained by considering no or full recycling of the landing stage. (2) A reusable space freighter of the Neptune class with an LEO capability of about 360 MT (*Koelle,* 1986) in a two-stage configuration to LEO will be employed. The third stage of this vehicle is an expendable space ferry flying directly from an 150-km injection altitude to the lunar surface in a one-way mission, also allowing full recycling or no recycling on the Moon. There will be no refueling in LEO or LUO and no reuse of the third stage doubling as a space ferry. (3) A fully reusable space transportation system with a two-stage space freighter will be employed between Earth's surface and LEO, a space ferry to be refueled in LUO with propellants delivered by the same vehicle to a lunar propellant depot, and continuing to the lunar surface with enough propellants to return to the LUO station after unloading its cargo on the Moon. No support in LEO will be required because the third stage will function as the space ferry. It can be characterized as a fully reusable system using Earth propellants only. (4) This is identical to mode (3), but with the assumption that lunar-produced LOX will be available either on the lunar surface or delivered from there to the LUO depot by a lunar tanker vehicle. This lunar tanker vehicle is more or less identical to the space

ferry (third stage) used for the LEO-LUO leg of the journey. (5) This is identical to mode (3), but with the assumption that all propellants required either on the lunar surface or in LUO are of lunar origin.

Assuming the specific impulse used for all space vehicles to be 4600 m/sec for LOX/LH_2 propellants, the propellant fractions were estimated to be between 0.88 and 0.92 depending on stage size. Velocity increments were close to 4100 m/sec for the LEO to LUO leg, and 1900 to 2000 for the lunar descent and ascent depending on engine burning times.

The results of the calculations are summarized in Table 1 and Fig. 1. It is easy to see that the big improvement comes, as expected, with the reuse of all vehicle hardware. Lunar propellants affect only the last leg and are desirable despite the fact that we have no return payload requirement. This is unrealistic, however, since a lunar base will have crew rotation requirements that will make the use of lunar propellants even more desirable. Thus, we can conclude that the step to have lunar propellants available only for the last leg of a one-way cislunar transportation system turns out to be ineffective. This fits very nicely in any evolutionary development scenario for a lunar base.

PASSENGER ROUND TRIPS

As shown in the previous section, lunar propellants are not decisive for one-way cargo missions because they can be used only for the LUO-to-lunar-surface leg. However, if there is heavy cargo delivered to the Moon, people have to be there to operate these facilities. This lunar crew will have duty cycles of several months or a year, depending on their physical and mental health. It is difficult at this stage of development to make predictions on the length of this duty cycle.

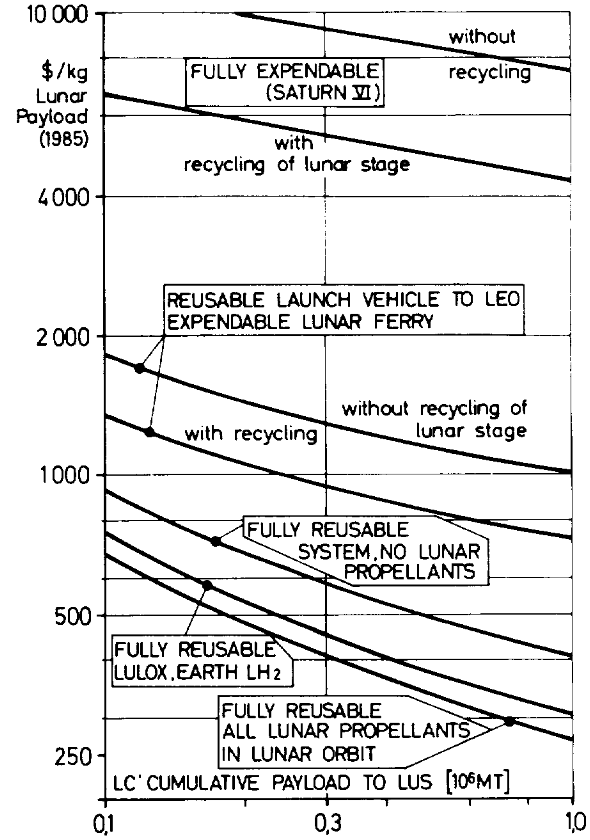


Fig. 1. One-way cargo flights, Earth's surface to lunar surface.

TABLE 1. Comparison of one-way mission modes.

Parameter		Dimension	Mission Mode: Saturn Expendable (1)	Reusable Launcher Expendable Ferry (2)	Fully Reusable System; Earth Propellants (3)	Fully Reusable System; Lunar LOX (4)	Fully Reusable System; All Lunar Propellants (5)
Ferry launch mass LEO		MT	140	360	360	360	360
Payload to LUO		MT	—	120	112	120	120
LUBUS launch mass LUO		MT	—	—	360	206	225
Payload to LUS		MT	20	70	195	100	120
Stage mass left on LUS		MT	14	28	—	—	—
Total cost per flight:		10^6 $					
at 0.1×10^6 MT - LC			229	128	177	75	81
at 0.3×10^6 MT - LC			186	93	112	44	49
at 1.0×10^6 MT - LC			151	72	78	30	32
Specific payload cost		$/kg					
at 0.1×10^6 MT - LC			6735	1310	910	753	672
at 0.3×10^6 MT - LC			5465	945	573	440	406
at 1.0×10^6 MT - LC			4438	734	402	301	263
Growth factor LEO to LUS		MT/MT	7.00	5.14	5.05	3.32	2.76
Growth factor with salvaging			4.12	3.67	—	—	—
Reduction of cost	0.1	%	100	19	14	11	10
With respect to	0.3		100	17	11	8	7
reference case (1)	1.0		100	16	9	7	6
Cost effectiveness of	0.1	%	—	—	100	83	74
lunar propellants	0.3		—	—	100	77	71
with respect to case (3)	1.0		—	—	100	75	65

Consequently, a lunar base will require a certain number of passenger round trips per annum as a function of facility size, production rates, and the growth rate of the lunar infrastructure. Previous studies (*Koelle*, 1982, 1986) have resulted in some relevant estimates for crew rotation requirements. A lunar base with a crew of about 500 persons indicates a relationship of 1 man-year for about 20 MT facility mass, a mass flow of lunar products of about 100 MT per man-year, and, with a one-year stay-time, 500 passenger round trips per year. Imports from Earth have been estimated to about 5 MT per man-year.

With such figures in mind, we have now to determine the cost burden of the crew rotation and its influence on the overall operation without and with lunar propellants. It is obvious that we have to transport people to the lunar surface with a manned spacecraft that can use the available lunar bus or a smaller special vehicle. In the case of Earth propellants only, we have to refuel the leg to LUO, and after arrival in the LUO propellant depot we have to take enough propellants on board to fly back to Earth or, alternatively, to the LEO station with the help of an aeroassist brake maneuver. Preliminary calculations indicate a lunar suface mass equivalent of about 4 MT per passenger flight in case of Earth propellants only. Translated into cost this amounts to about $\$1.25 \times 10^6$/round trip (1985) at the given volume. If lunar liquid oxygen (LULOX) were available, the mass burden would be reduced by about 40% and the price for one round trip will be on the order of $\$0.5 \times 10^6$/round trip, in the case of a fairly large lunar base.

Since these figures are preliminary in nature, there will be variables with respect to base size and mission modes employed. The size of the passenger transporting spacecraft will be another factor influencing the round-trip price. A more detailed scenario for the evolutionary build-up of the lunar base is required to come up with more precise figures.

TRANSPORTATION COSTS FOR LUNAR EXPORTS

Exports presently envisioned from a lunar factory are feedstocks, construction materials, LOX, and selected products that are not labor intensive. The place where these could be used is the GEO for manufacturing and assembling space solar power plants (*Koelle*, 1987).

The transportation task would be carried out by a space ferry vehicle that would be refueled in LUO. The fuel may come from the Earth (LH_2) or partly from the lunar surface (such as aluminum powder). The LULOX and fuel would arrive in LUO by special tanker flights (*Matijevic*, 1987).

Thus, we would like to compare the following mission modes: (1) A space freighter that operates from Earth with Earth-produced propellants without the assistance of lunar resources. This brings up all cargo required in GEO. The launch vehicle is a fully reusable three-stage vehicle taking off from a near-equatorial launch site in a direct flight mode bypassing the LEO station (*Koelle*, 1986). This mode is the basis for comparison of the effectiveness of a lunar-supported logistic system. (2) A lunar-based space ferry serves the legs from the lunar surface to LUO and after refueling there, the leg from LUO to the GEO. It takes return propellants along to GEO for getting back to LUO where it is refueled again. In this mode, the LH_2 comes by tanker flights from the Earth space port directly to the LUO propellant depot, and the LOX is delivered to LUO from the lunar surface by a special tanker ferry of the same size as the cargo ferry. (3) This is the same as mode 2 except that 50% of the fuel is lunar-produced aluminum with a loss in performance (3900 m/sec instead of 4600 m/sec). (4) The lunar-based ferry receives all propellants from lunar resources, assuming that hydrogen and oxygen can be produced by lunar factories in sufficient quantities at acceptable prices. The space ferries themselves and their spare parts are supplied by Earth manufacturers, however. Maintenance and repair services are offered at all transportation nodes (lunar surface, LUO, and GEO). This mode represents the most optimistic operational conditions for space vehicles using chemical propellants.

The assumptions used to make the calculations are as follows: (1) life cycle payload deliveries to GEO = 0.3 to 3.0×10^6 MT; (2) 100 reuses for each ferry vehicle; (3) initial mass of space ferry in LEO or LUS = 360 MT; (4) exhaust velocities = 3900 to 4600 m/sec respectively; (5) single-flight payload capability to GEO from Earth = 90 MT; and (6) empty space ferry vehicle with heat shield = 35 MT.

The results of the calculations are presented in Table 2 and Fig. 2. At the lower end of the payload spectrum we have values of about $550/kg for mode 1 and about $150/kg for mode 3, using a great amount of lunar-produced propellants. For the higher payload volumes we obtain specific transportation costs of about $260/kg and $70/kg respectively. This shows the attractiveness of employing lunar propellants for ferrying lunar exports to GEO.

SUMMARY

The production of propellants from lunar resources is the most valuable commodity that can be produced on the Moon. This is obvious because it will cost about $10,000/kg during the build-up of a lunar outpost to deliver lunar facilities, consumables, and return propellants. This analysis indicates that the introduction of fully reusable systems can reduce the specific transportation cost from Earth to the lunar base to $2000/kg and at large volumes even close to $1000/kg. The use of lunar-produced oxygen in such a space transportation system has the potential of getting the transportation cost down to $500/kg or less. The gain of hydrogen production on the Moon is modest in the case of one-way transportation, but very important for return trips when rotating lunar crews. Using aluminum, even at reduced engine performance, promises to cut the round-trip costs to less than half.

If and when the delivery of raw materials and feedstock to the GEO construction site of space solar power plants develops into a major market, the production of lunar propellants becomes even more important. This analysis indicates specific transportation cost from the lunar surface to GEO on the order of $300/kg at a cumulative payload volume of 0.3×10^6 MT using LULOX only, which comes down to about $150/kg using a 50:50 Al/LH_2 mixture if the aluminum is produced on the Moon. At cumulative life-cycle payload volumes of 3.0×10^6 MT from the lunar surface to GEO, the specific transportation cost may be reduced to $70/kg. This assumes an average ΔV value of 3000 m/sec for the LUO-to-GEO leg. This analysis made the additional assumption that there are no other demands on the launch vehicle and space ferry, which is a conservative assumption. Consequently, there is some hope that the specific transportation cost from the Moon to GEO may be as low as $50/kg (1985) in a high density market. This would be only about one third of the specific transporation cost of an equivalent mass from the Earth's surface to GEO. This difference might determine whether or not space solar power systems become economically feasible.

TABLE 2. Comparison of lunar surface to GEO mission modes.

Parameter	Dimension	Mission Mode: ES-GEO-ES; Earth Propellants	LUS-LUO-GEO and Return; LULOX/ Earth LH_2	All Lunar Propellants LUS-LUO-GEO and Return; LULOX/50% LUAL	All Lunar Propellants LUS-LUO-GEO and Return; LULOX/ $LULH_2$
Ferry launch mass LEO Ferry launch mass LUS	MT	360	360	360	360
Payload to GEO	MT	90	154	107	135
Cost launch vehicle per flight	10^6\$				
at 0.3×10^6 MT - LC		41.8	43.5	(146)	(146)
at 1.0×10^6 MT - LC		28.1	27.0	(70)	(70)
at 3.0×10^6 MT - LC		21.6	18.3	(43)	(43)
Cost of ferry per flight	10^6\$				
at 0.3×10^6 MT - LC		7.0	7.4	13.0	13.2
at 1.0×10^6 MT - LC		3.5	5.2	9.8	10.1
at 3.0×10^6 MT - LC		1.8	4.2	7.7	8.1
Lunar-produced propellant per flight	MT	0	191	541	486
Cost per flight mission	10^6\$				
at 0.3×10^6 MT - LC		48.8	50.9	13.9	16.6
at 1.0×10^6 MT - LC		31.6	32.2	11.3	11.7
at 3.0×10^6 MT - LC		23.4	22.5	8.6	9.1
Specific transportation cost to GEO	\$/kg				
at 0.3		542	331	150	123
at 1.0		351	210	106	87
at 3.0		260	145	80	67

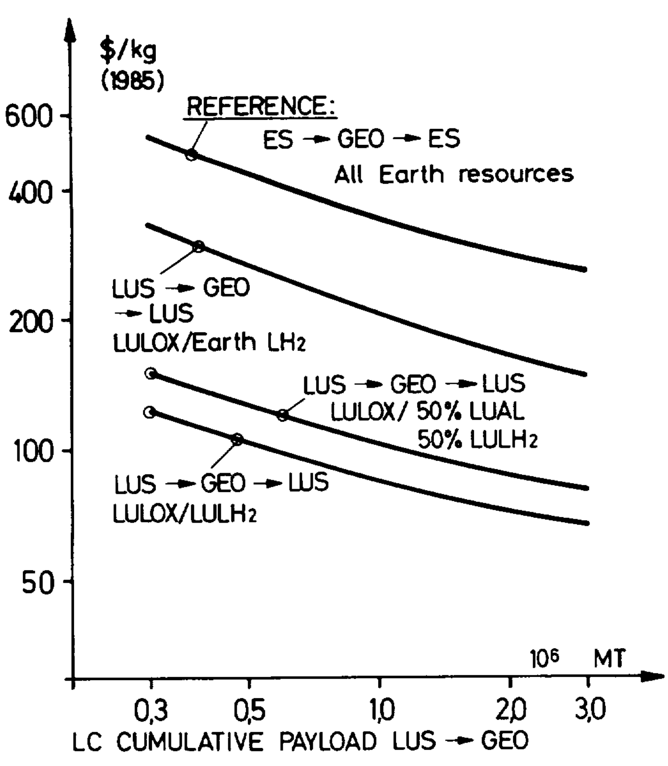


Fig. 2. Specific transportation cost of cargo from lunar surface to GEO.

REFERENCES

Bock E. H. (1979) Lunar Resources Utilization for Space Construction. Final Report. *NASA Contract NAS-9-15560.* General Dynamics Convair Division, San Diego, CA. 3 vols.

Cole D. M. and Segal R. (1964) Rocket propellants from the Moon *Astronaut. Aeronaut., 9,* 56-63.

Crabb T. M., Teeter R. R., and Johnson L. R. (1986) Lunar based propulsion systems. *Proc. First Lunar Development Symposium 1986.* Atlantic City, New Jersey.

Fairchild K. and Roberts B. (1986) Modelling and simulation of a lunar base and associated space transportation system. *Proc. First Lunar Development Symposium 1986.* Atlantic City, New Jersey.

Koelle H. H. (1986) Space transportation—The key to the utilization of extraterrestrial resources. *IAA-86-458,* 37th IAF Congress, Innsbruck.

Koelle H. H. (1987) On the life cycle cost and return on investment of a 500 GW global space solar power system. *IAF-87-249,* 38th IAF Congress, Brighton.

Koelle H. H. and Johenning B. (1982) Lunar base simulation. *Tech. Note No. 115,* Techn. University of Berlin.

Koelle H. H. and Johenning B. (1986) Evolution and logistics of an early lunar base. *Acta Astronaut., 13,* 527-536.

Koelle H. H. et al. (1987) The case for an international lunar base. *Acta Astronaut., 17,* 463-489.

Matijevic Z. (1987) Analyse und Entwurf einer universellen Raumfähre für grosse Frachtraketen. Master's thesis, Techn. Univ. of Berlin.

Paine T. O. et al. (1986) *Pioneering the Space Frontier.* Bantam Books, New York. 211 pp.

Ride S. K. (1987) *Leadership and America's Future in Space: A Report to the Administrator.* U.S. Govt. Printing Office, Washington, DC. 63 pp.

Stehling K. R. (1958) Moon refueling for interplanetary vehicles. *Aviation Age, 29,* 22-23, 180.

Thomas U. (1984) Analyse cis-lunarer Raumtransportsysteme mit michtkonventionellen Antrieben unter besonderer Berücksichtigung der Lebenszykluskosten. Ph.D. dissertation, Techn. Univ. of Berlin. 227 pp.

Zurawski R. L. (1986) *Current Evaluation of the Tripropellant Concept.* NASA TP-2602. 30 pp.

IMPACT OF LUNAR OXYGEN PRODUCTION ON DIRECT MANNED MARS MISSIONS

N93-13984

Roy M. Young Jr.[1] **and William B. Tucker**[2]

SRS Technologies
990 Explorer Blvd.
Huntsville AL 35806

A manned Mars program made up of six missions is evaluated to determine the impact of using lunar liquid oxygen (LOX) as a propellant. Two departure and return nodes, low Earth orbit and low lunar orbit, are considered, as well as two return vehicle configurations, a full 70,000-kg vehicle and a 6800-kg capsule. The cost of lunar LOX delivered to orbit is expressed as a ratio of Earth launch cost.

LIST OF ACRONYMS

TLI	Trans Lunar Injection
LOI	Lunar orbit insertion
TMI	Trans-Mars injection
MOI	Mars orbit insertion
TEI	Trans-Earth injection
EOI	Earth orbit insertion
EEC	Earth departure and Earth return capsule vehicle
EEF	Earth departure and Earth return full vehicle
LEC	Lunar departure and Earth return capsule vehicle
LEF	Lunar departure and Earth return full vehicle
LLC	Lunar departure and lunar return capsule vehicle
LLF	Lunar departure and lunar return full vehicle
ECCV	Earth crew capture vehicle
MTV	Mars transfer vehicle
ETV	Earth transfer vehicle
LEO	Low Earth orbit
LOX	Liquid oxygen
LH_2	Liquid hydrogen
LLO	Low lunar orbit

INTRODUCTION

As part of the SRS Manned Mars Mission and Program Analysis Study conducted for Marshall Space Flight Center, a series of manned Mars programs was investigated, each culminating with a manned base on Mars. Initial guidelines and assumptions for the study specify the 1999-2035 timeframe and that each program would include an exploratory, outpost, and base phase. The first three manned missions of each program were considered site survey missions. The outpost phase was reached when a portion of the crew had the option of remaining at Mars between missions. The base phase was accomplished when there was a permanently manned facility on the surface of Mars.

As Fig. 1 shows, each of the five example programs emphasized different objectives. The Early (or Reference) Program takes advantage of the cyclic nature of Earth-Mars oppositions (see Fig. 2) to accomplish the shorter exploratory missions near the oppositions when Mars is at perihelion, and represents a fairly vigorous program to reach milestones as soon as possible. The Phobos/Deimos Program has initial landings on the surface of the martian moons and later excursions to the surface of Mars. The Split/Sprint Program uses split missions with cargo vehicles sent on long, low-energy trajectories, and the lighter manned modules sent on shorter, high-energy trajectories. The Mid-Range Program delays the start of a manned Mars program while additional emphasis is placed on low Earth orbit (LEO) activities. The Later Program delays the missions for one cycle of oppositions, approximately 15 years, and includes a lunar emphasis program for the years 1999-2018. This paper investigates the possible benefits of a lunar liquid oxygen (LOX) propellant plant on the Later Manned Mars Program.

Studies on the impact of lunar LOX production on Mars missions have been conducted by several authors (*Keaton*, 1985; *Babb and Stump*, 1986; *Cordell and Wagner*, 1987). These studies have all been based on conjunction class "minimum energy" missions. Conjunction missions use low-energy near-Hohmann transfer trajectories, which cause flight times to Mars to be on the order of eight months each way. Waiting at Mars for a near-Hohmann return opportunity requires stay times at Mars of 300 to 550 days. Thus the total mission time for a conjunction class mission is 2.5 to 3 years. Conjunction class missions provide the most efficient use of propellants when transporting large amounts of material to and from Mars. Sensitivity studies (*Davis*, 1986) have shown that the conjunction class mission can deliver four times the payload on a round-trip mission or six times the one-way payload from Earth orbit to Mars orbit than the opposition class mission (with the same initial mass in LEO and propulsion technology). The disadvantage of the conjunction class mission lies in the long total trip time that can be debilitating on the crew and increase propellant boil-off losses. For this reason the opposition class mission is important in planning Mars programs. The opposition class trajectory is characterized by 30-90-day stay times at Mars and total trip times from 450 to 730 days. This paper considers opposition class missions for the manned exploratory and early outpost phases of the program and

[1]Now at Mail Stop EO24, Marshall Space Flight Center, Huntsville AL 35812
[2]Member of The Technical Staff, Nichols Research Corp., 4040 S. Memorial Parkway, Huntsville AL 35806

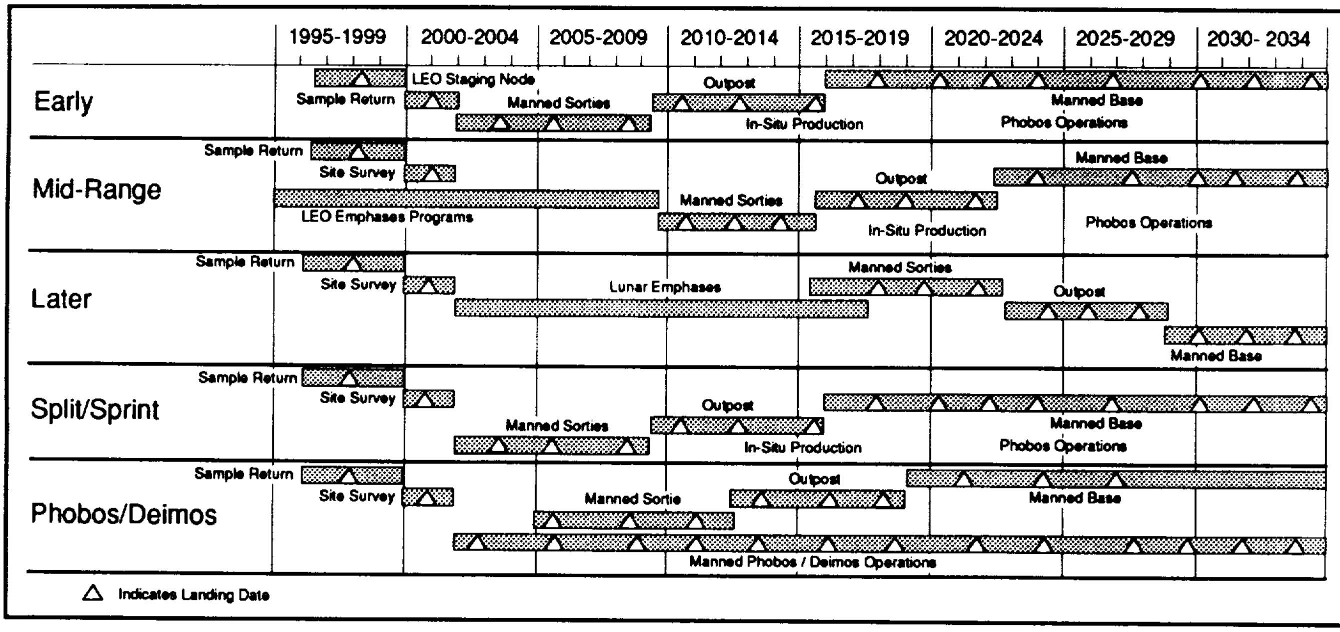


Fig. 1. Example of the manned Mars mission programs.

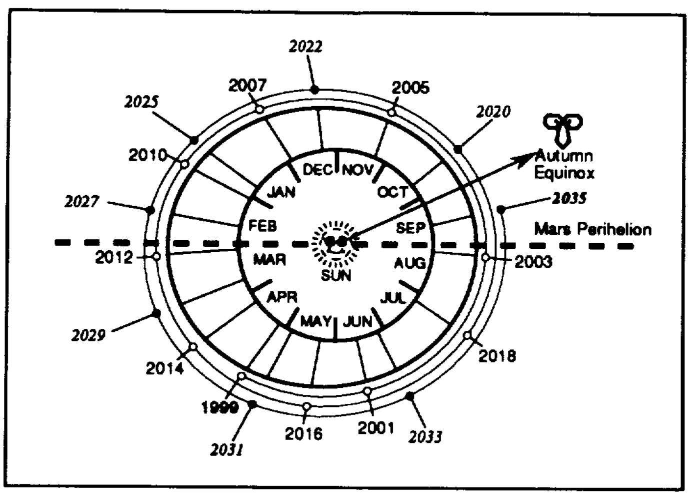


Fig. 2. Earth-Mars oppositions.

conjunction class missions for the later outpost and base phases of the program. Table 1 details the missions required to accomplish the program with the payloads carried on each mission.

COMPARATIVE SCENARIOS

The LOX propellant required for the various missions in the Later Program was assumed to be produced on either the Earth or the Moon. In either case a 500-km circular space station orbit is used as a staging area for assembly of the Mars transfer vehicle (MTV). If the LOX is produced on the Earth the trans-Mars injection (TMI) burn is initiated from the LEO staging orbit. If the LOX is produced at a lunar propellant plant the MTV is loaded at the staging area with all the liquid hydrogen (LH_2) required for the mission, including the lunar operations, and with enough LOX to initiate the translunar injection (TLI) and lunar orbit insertion (LOI) maneuvers. The ΔVs for these burns are 3.155 km/sec and 0.975 km/sec respectively (*Babb and Stump,* 1986). The resulting lunar orbit is a 500-km circular orbit. This study assumes that the lunar LOX is available in the same orbit. The MTV is then

TABLE 1. Mission characteristics for the "Later" Program.

Mission Number	Mission Class	Opposition Year	Trip Time in Days	Stay Time in Days	Payloads
1	Manned opposition	2018	450	60	130,000 kg
2	Manned opposition	2020	550	60	130,000 kg
3	Manned opposition	2022	730	90	130,000 kg
4	Manned opposition	2025	730	90	178,000 kg
5a	Manned opposition	2027	730	90	130,000 kg
5b	Cargo conjunction	2026	220	NA	100,000 kg
6	Manned conjunction	2029	1000	500	230,000 kg

tanked up with the lunar LOX and the TMI operation is initiated. The optimum time for lunar departure is at a full Moon when the velocity vectors for the Earth and Moon are in the same direction. All departures from and returns to the Moon were therefore constrained to occur at the time of the nearest full Moon.

The MTV used in this analysis is a three-stage system with each stage's propulsion system having an I_{sp} of 482 sec. The propellant used is a mixture of LOX and LH_2 with a mixture ratio of 6:1. The first stage performs the TMI burn and is then expended. The second stage performs a 25 m/sec midcourse correction, the Mars orbital insertion (MOI), and trans-Earth injection (TEI) maneuvers. The MOI maneuver is accomplished with an aerobrake provided the C3 at Mars is less then 50 km/sec, otherwise a propulsive burn is required to reduce the C3 to 50 km/sec. A 24-hr 500-km periapsis highly elliptical parking orbit around Mars was assumed to accommodate Mars landing operations and minimize departure ΔV requirements. After the appropriate stay time at Mars, the second stage is ignited to perform the TEI. Following this burn the second stage is expended and the Earth transfer vehicle (ETV) utilizes the third stage for a midcourse burn of 25 m/sec.

At this point in the analysis two return vehicle configurations are investigated. A full module return brings back the entire ETV with a mass of 70,000 kg. A capsule return expends the ETV and crew return is completed in a small Apollo-type Earth crew capture vehicle (ECCV) with a mass of only 6800 kg. Two return nodes are also investigated in the study: return to a 500-km circular low lunar orbit (LLO) or return to a 24-hr 500-km perigee highly elliptical Earth orbit. If the ETV or ECCV is returned to Earth orbit, an aerobrake is assumed for the Earth orbit insertion (EOI) maneuver if the C3 at Earth arrival is less then 25 km/sec. If the C3 is greater than 25 km/sec the EOI maneuver is performed propulsively by the third stage. In both the full return and capsule return to the lunar orbit, the LOI is performed by the third stage. As was the case with lunar departure, return to the Moon is accomplished at a full Moon to minimize the ΔV requirements. Figure 3 depicts the various options available for departure and return nodes.

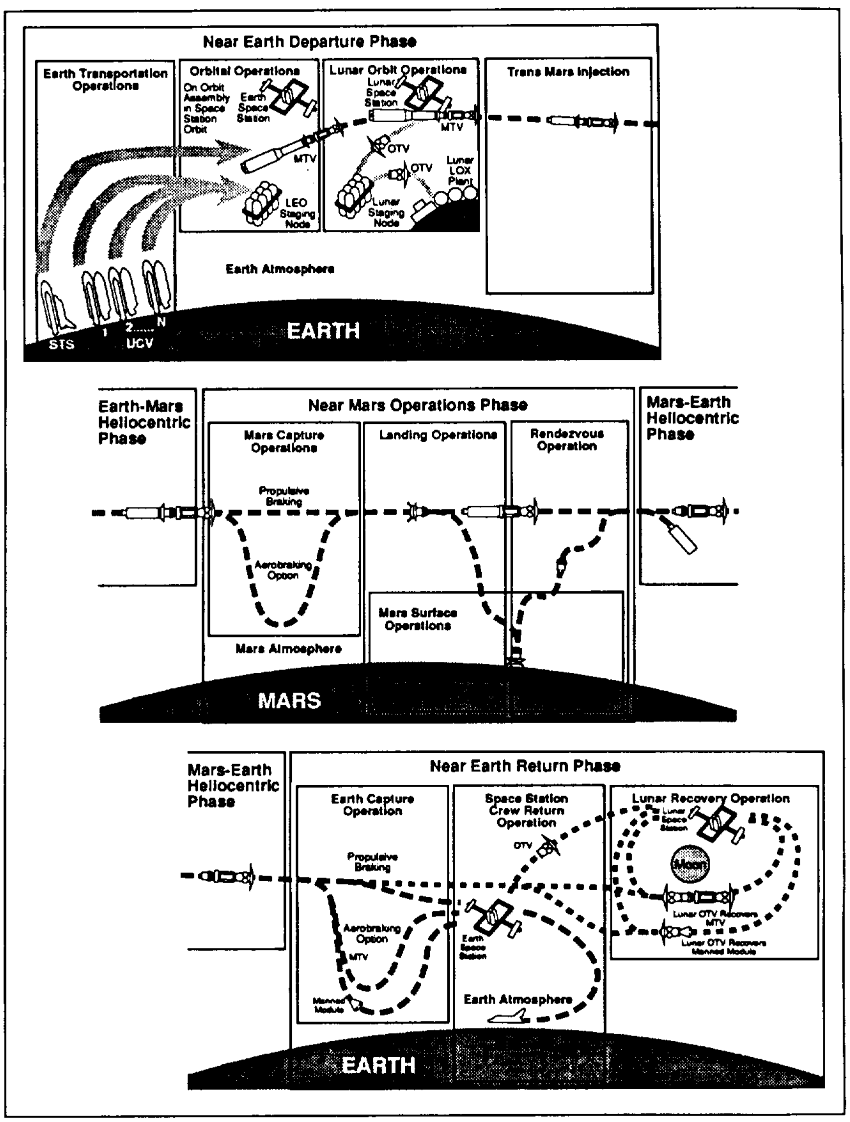


Fig. 3. Options available for departure, arrival, and return nodes.

RESULTS AND CONCLUSIONS

The total trip time, stay time at Mars, and payload masses required for each mission are inputs to the SRS trajectory analysis code. Using Lambert's theorem to calculate ΔV requirements, the program determines the trajectory, fuel requirements, and vehicle size to minimize the mass in LEO or LLO, depending on departure point. If a lunar departure is planned, the fuel requirements for the TLI and LOI are also calculated and charged to the mass required at the LEO staging orbit. The results of these calculations are presented in Fig. 4. Note that the mass of the payload is not included in the total mass since it is constant for each mission. As can be seen from Fig. 4 there is a wide variation in the total mass required to accomplish each mission in the Later Program. This is due to the different payloads carried (see Table 1) and the oppositions variations in Earth/Mars (see Fig. 2). As would be expected, the capsule returns are the best options due to the much smaller mass of the ECCV. In addition, the initial mass required in LEO for lunar departure, including the extra propellants for TLI and LOI, are generally less than the mass in LEO required for direct missions from the Earth to Mars. The lunar departure-Earth return options provide the best performance since the ΔV requirements for TMI are smaller when departing from lunar orbit and the ΔV requirements at Earth return are smaller due to the higher orbital velocity in LEO. The lunar departure-lunar return options are generally the worst, due

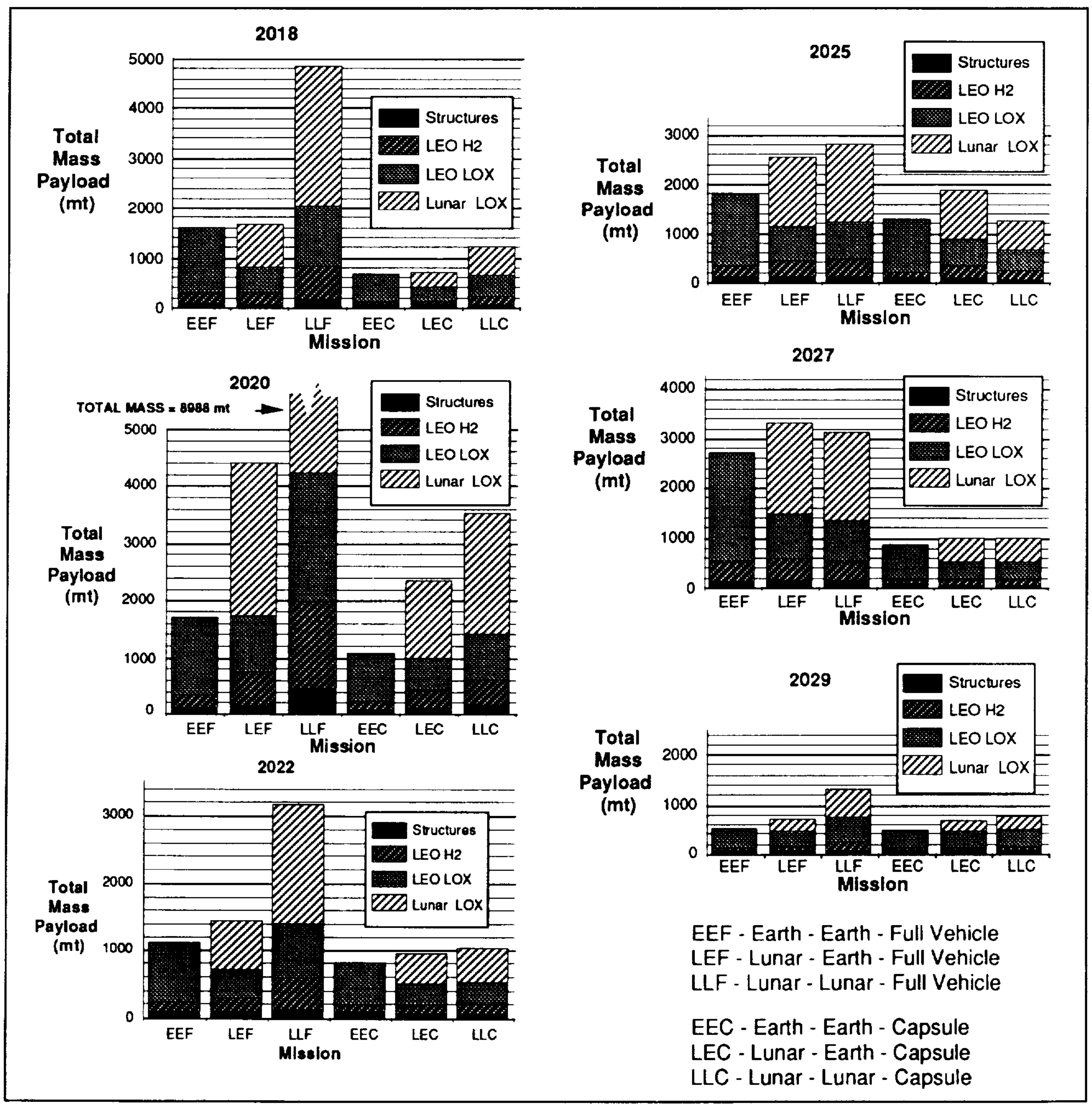


Fig. 4. Mass requirements for missions in the "Later" Program (1 mt = 1000 kg).

primarily to the large ΔV maneuver required to place the vehicle in LLO upon return. Figure 5 shows ΔV requirements for the different missions and options.

Determining the cost savings incurred by using lunar LOX is a difficult task. The total cost of LOX in LEO is dominated by the Earth surface to LEO transportation cost, with manufacturing cost being negligible. The transportation cost of lunar LOX should be less, based on the smaller gravitational field; however, the manufacturing cost should be higher due to the harsh lunar environment. This paper has assumed that LOX is present in both LEO and lunar orbit without looking at the manufacturing and transportation cost. But a relative cost ratio of lunar LOX to LEO LOX can be assigned, as shown in Fig. 6. For example, if you save 400,000 kg of total propellant in LEO by going to the Moon and picking up 800,000 kg of lunar LOX, then the relative cost ratio of the lunar LOX is 0.5. In cases where the additional LOX and H_2 required in LEO to push the MTV to lunar orbit is greater than the LEO savings incurred by the use of lunar LOX, it is not clear there is a savings and these missions are assigned a value of 0 in Fig. 6. The results to date are inconclusive as to the viability of lunar LOX for use in direct manned Mars missions. Additional study in the areas of propellant production on the Moon and lunar surface to orbit transportation systems must be conducted before it can be determined if relative cost ratios such as those shown in Fig. 6 are technologically feasible. As the definition of the lunar base progresses and Mars mission planning matures, lunar LOX propellant production should be analyzed in the framework of total program life cycle cost.

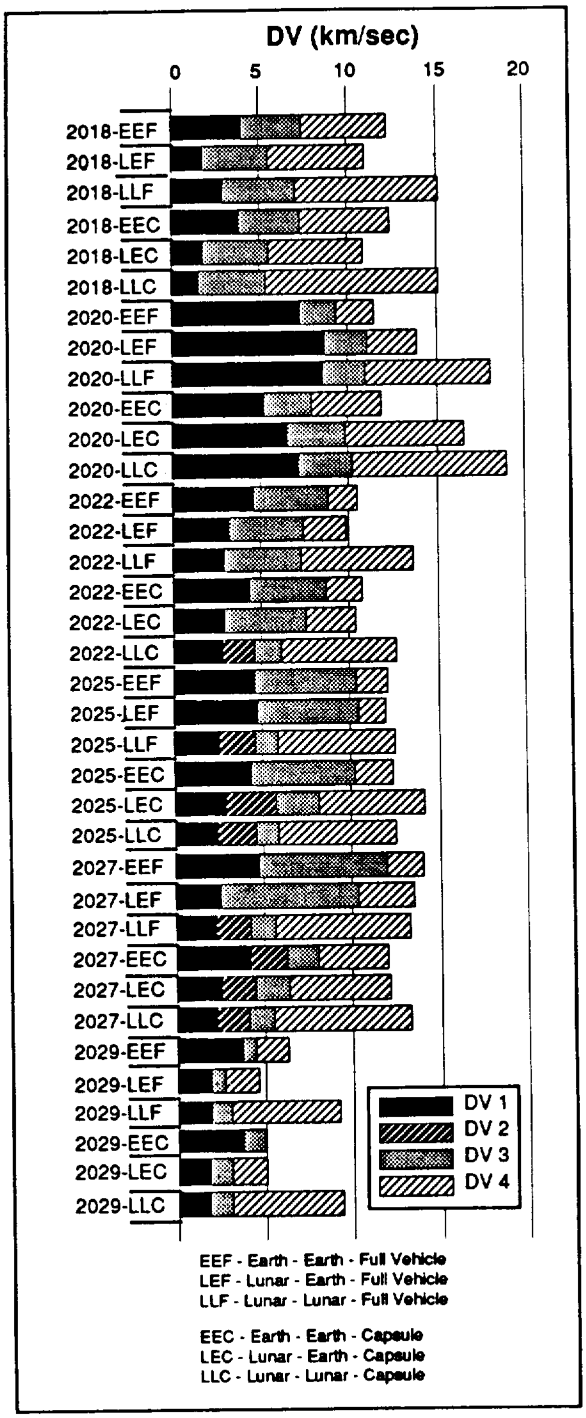


Fig. 5. Delta V requirements for "Later" Program options.

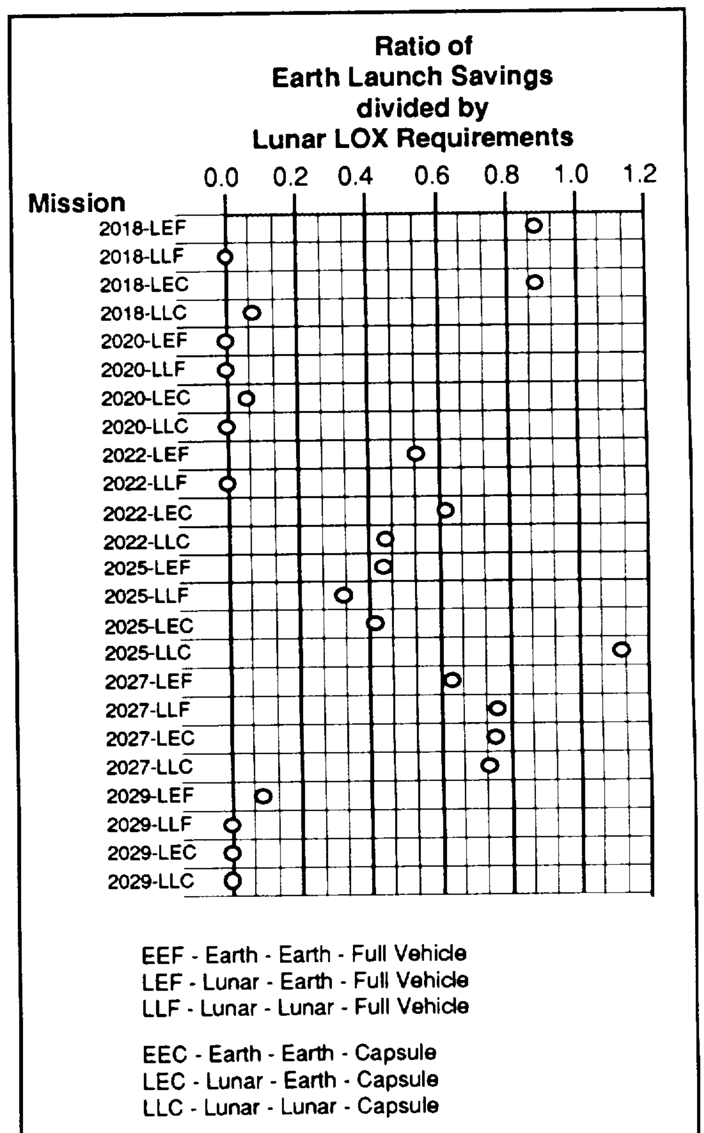


Fig. 6. Lunar launch cost relative to Earth launch cost.

NOTE IN PROOF

This paper presents results only for "direct" manned Mars missions, i.e., those without gravity assists and without considering libration point basing options. Several papers have been published since this paper was presented that give insight into benefits to be gained from both gravity assist and from libration point basing options. These publications are now included in the bibliography of this paper. All these papers are somewhat qualitative in nature, and it is evident that more refined total life cycle cost analyses must be accomplished before one basing option can be designated as optimum for performing manned Mars missions.

REFERENCES

Babb G. and Stump W. (1986) Use of lunar produced propellants for manned Mars missions. In *NASA Manned Mars Study M002, Vol. 1*, pp. 188-200. NASA, Washington, DC.

Cordell B. and Wagner S. (1987) *Possible Resource Synergisms Between Mars Programs and Earth-Moon Activities.* General Dynamics Space Systems Division, San Diego, California. 22 pp.

Davis H. (1986) A manned Mars mission concept with artificial gravity. In *NASA Manned Mars Study M002, Vol. 1*, pp. 292-302. NASA, Washington, DC.

Keaton P. W. (1985) *A Moon Base/Mars Base Transportation Depot.* Los Alamos Natl. Lab. Rept. LA-10552-MS. 14 pp.

BIBLIOGRAPHY

Andrews D. G. and Snow W. R. (1981) The supply of lunar oxygen to low Earth orbit. In *Papers Presented at the Princeton Space Manufacturing Conference IV*, pp. 173-179. AIAA, New York.

LANL/NASA (1986) *Manned Mars Missions* (two-volume technical report of NASA and Los Alamos National Laboratory studies), NASA M002.

Snow W. R., Kubby J. A., and Dunbar R. S. (1981) A small-scale lunar launcher for early lunar materials utilization. In *Papers Presented at the Princeton Space Manufacturing Conference IV*, pp. 157-171. AIAA, New York.

Woodcock G. R. (1985) Transportation networks for lunar resources utilization. In *Space Manufacturing 5: Engineering with Lunar and Asteroidal Materials*, pp. 89-96. AIAA, New York.

Woodcock G. R. (1986a) Logistics support of lunar bases. *IAA-86-511*, 37th IAF, Innsbruck, Austria.

Woodcock G. R. (1986b) Economic potentials for extraterrestrial resources utilization. *IAA-86-451*, 37th IAF, Innsbruck, Austria.

Woodcock G. R. (1988a) Modular evolutionary system architectures for exploration missions. In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century*, p. 258. Lunar and Planetary Institute, Houston.

Woodcock G. R. (1988b) *Basing Options for Lunar Oxygen for Manned Mars Missions.* Boeing Aerospace, Huntsville. 14 pp.

N93-1 ̈98

FUSION ENERGY FROM THE MOON FOR THE TWENTY-FIRST CENTURY

G. L. Kulcinski, E. N. Cameron, J. F. Santarius, I. N. Sviatoslavsky, and L. J. Wittenberg

Fusion Technology Institute
University of Wisconsin
1500 Johnson Drive
Madison WI 53706

H. H. Schmitt

P.O. Box 14338
Albuquerque NM 87191

INTRODUCTION

Modern societies depend on energy for their very existence. Without it, the Earth cannot support its present population of 5 billion people, let alone even dream about supporting the 8 to 10 billion people that are likely to inhabit the Earth under the so-called "equilibrium" conditions (*Kefitz,* 1977) in the twenty-first century. Society has long passed the time when most humans can "live off the land." At the present time, the average primary energy consumption is slightly over 2 kW per capita (*Hafele,* 1981; *U.S. Department of Energy,* 1987), but over 70% of the world's population is well below that average and is desperately trying to improve its standard of living. Therefore, copious amounts of energy will be needed over the next century to feed, clothe, warm, cool, protect, and keep the Earth's citizens healthy in the face of an environment under increasing stress.

Ever since the world population passed the one billion mark in 1830, fossil fuels such as coal, oil, and natural gas have been used to sustain life on this planet. Up through 1986, we have used approximately 300 TW-yr of that energy (1 TW-yr = 10^{12} W for one year). Our present world population of 5 billion people (up from 2 billion in 1930, 3 billion in 1960, and 4 billion in 1975) and a usage rate of ~2 kW/capita, means that we are currently using primary energy at a rate of ~10 TW-yr/yr. As the world moves toward the "equilibrium" population of 8 to 10 billion people, and allowing for some modest increase in the standard of living for the underdeveloped nations, our future worldwide primary energy consumption rate will be between 20 and 30 TW-yr/yr. Since there is only 1000-1500 TW-yr of fossil fuel energy left that is economically recoverable (*Hafele,* 1981; *U.S. Department of Energy,* 1987), it is easy to see that somewhere in the mid-twenty-first century our economically recoverable fossil fuel resources will be exhausted. It is also possible that environmental problems such as acid rain, the CO_2 "greenhouse" effect, or wars over the last remaining deposits of fossil fuels will limit the useful lifetime to even less than that determined by resources alone. It is also important to note that fossil fuels will also be of increasingly greater value as chemical feedstocks for nonfuel products to sustain the quality of life. In any case, for much of the twenty-first century, inhabitants of the Earth will have to rely on renewable energy sources (solar, wind, hydro, geothermal, and biomass) and nuclear energy sources to survive.

The use of nuclear energy in the form of fission reactors is already widespread with nearly 400 reactors located in 26 countries that provide approximately one-sixth of the world's electricity. By the year 2000, this fraction will increase to approximately one-fifth. However, this source of energy is not without its problems, which currently range from public resistance to the storage of long-lived fuel cycle wastes to reactor safety questions.

There is another form of nuclear energy that could provide an even more environmentally acceptable and safer solution to our long-range energy problems. The fusion of certain light elements into heavier ones at high temperatures can release enormous amounts of energy. This form of energy release can be observed every day from the sun, and every night from the billions upon billions of stars that themselves are powered by fusion reactions.

Scientists have been trying to reproduce a controlled fusion reaction here on Earth since 1951. After 40 years of research and the expenditure of over 20 billion dollars in a worldwide program, the fusion community is now within a few years of the first "breakeven" fusion experiments (*Hawryluk et al.* 1986), historically similar in some ways to the Chicago Stagg Field fission reactor experiment conducted by Enrico Fermi and his colleagues in 1941 (*Fermi and Szilard,* 1944). Early in the 1990s, magnetically confined plasmas in either the TFTR device at Princeton, USA (*Hawryluk et al.,* 1986) or the JET device in Culham, UK (*JET Team,* 1986) are expected to release more thermonuclear energy than required to initiate the fusion reaction.

Scientists have already anticipated success in these devices and have designed the next generation of fusion devices that will produce hundreds of megawatts of thermonuclear power in the 1990s (*Abdou et al.,* 1986). Work has even begun on the design of conceptual commercial fusion power plants (*Kulcinski,* 1985; *Hogan and Kulcinski,* 1985) and for fusion power sources in space (*Santarius et al.,* 1987).

Currently, the worldwide effort in fusion is concentrating on the deuterium (D) and tritium (T) reaction because it is the easiest to initiate. However, 80% of the energy released in this reaction is in the form of neutrons and these particles not only cause severe damage to the surrounding reactor components, but they also induce very large amounts of radioactivity in the reactor structure.

It is fortunate that there is another fusion reaction, involving the isotopes of D and helium-3 (He^3) that, in theory, involves *no* neutrons or radioactive species, i.e.

$$D + He^3 \rightarrow p(14.7)\ MeV) + He^4\ (3.7\ MeV) + 18.4\ MeV$$

However, some side DD reactions do produce neutrons and as little as 1% of the energy released in this reaction could be released in the form of neutrons. Such a low neutron production

(compared to the DT cycle) greatly simplifies the safety-related design features of the reactor and reduces the levels of induced radioactivity such that extensive radioactive waste facilities are not required. Furthermore, since approximately 99% of the energy can be released in the form of charged particles, this energy can be converted directly to electricity via electrostatic means (similar to running a charged particle accelerator backwards) with efficiencies of 70-80%.

If this reaction is so advantageous, why has it not been pursued more vigorously in the past? The simple answer is that there is no large terrestrial supply of He^3. The amount of primordial He^3 left in the Earth is on the order of a few hundred kilograms (*Wittenberg et al.,* 1986) and the He^3 that results from the decay of man-made tritium ($t_{1/2} = 12.3$ yr) is also only being produced at a rate of 10-20 kg/yr. Since the energy equivalent of He^3 is 19 MW-yr per kg, one can see that to provide a significant fraction of the world's energy needs would require hundreds of *tonnes* of He^3 per year, not hundreds of kilograms per year.

What is the solution? In 1986, it was pointed out by scientists at the University of Wisconsin (*Wittenberg et al.,* 1986) that over the four-billion-year history of the Moon, several hundred million metric tonnes of He^3 have impacted the surface of the Moon from the solar wind. The analysis of Apollo and Luna retrieved samples showed that over 1,000,000 tonnes of He^3 still remain loosely imbedded in the surface of the Moon. It will be shown later in this report that even a small fraction of this He^3 could provide the world's electricity needs for centuries to come.

The main object of this paper is to show how commercial D-He^3 fusion reactors can impact the twenty-first century. After an initial discussion of the physics of this fusion cycle, a brief description of current experiments dealing with D-He^3 will be given. The technology issues of safety, availability, reliability, maintainability, radioactive wastes, and costs will then be addressed. The cost of electricity and development pathway for this fusion cycle will then be discussed. Finally, the question of fuel supply will be examined.

THE PHYSICS OF THE D-He^3 FUSION REACTION

When certain light isotopes are heated to an extremely high temperature and confined in a small region of space, they can react with each other, producing particles that weigh less than the reactants. The missing mass is converted into energy. The reaction rate of selected fusion fuels is plotted in Fig. 1 and reveals that the DT reaction occurs at the lowest temperatures. Figure 1 also shows that as the temperatures are increased above 10 keV (1 keV is roughly equivalent to 10,000,000 K), the DD, then the D-He^3, reactions become significant. For various physics and engineering reasons, the optimum temperature at which to run these reactions ranges from 20 keV for the DT reaction to 60 keV for the D-He^3 plasmas.

It was pointed out earlier that the presence of D atoms in a D-He^3 plasma can result in DD reactions as well as D-He^3 fusions. The DD reactions are listed below and each occurs with roughly equal probability.

$$D + D \rightarrow p + T = 4.0 \text{ MeV}$$

$$D + D \rightarrow He^3 + n + 3.3 \text{ MeV}$$

Not only does one of the DD branches produce a neutron, but some of the T produced by the other branch can also burn with

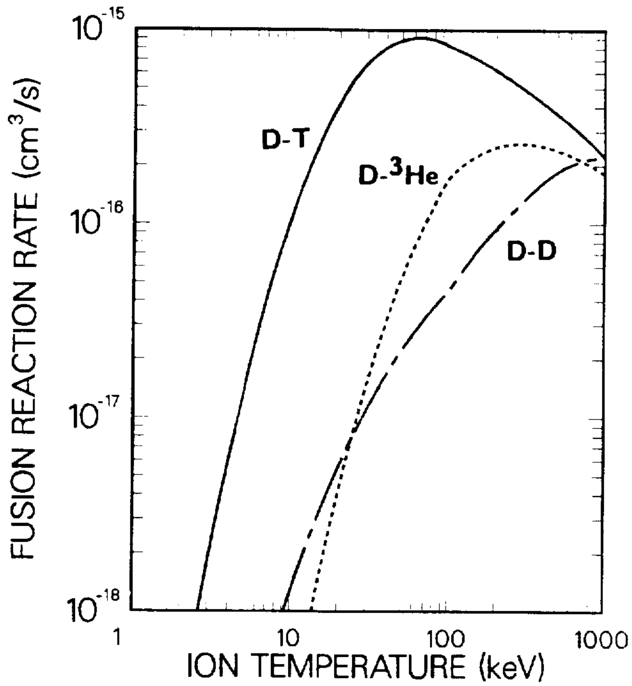


Fig. 1. Major fusion fuel reactivities.

D by the following reaction

$$D + T \rightarrow n + He^4 + 17.6 \text{ MeV}$$

The ratio of power released in the form of neutrons compared to that released in the D-He^3 fusion is then given as

$$\frac{P_n}{P_{D\text{-}He^3}} = (\text{Constant}) \left(\frac{n_D}{n_{He}}\right) \left(\frac{<\sigma v>_{DD}}{<\sigma v>_{DHe}}\right)$$

where n_D, n_{He} = number densities of D and He^3, respectively; $<\sigma v>_{DD}$ = fusion reaction rate of D ions; $<\sigma v>_{DHe}$ = fusion reaction rate of D ions and He^3 ions; and Constant (at 60 keV) ~0.03 if none of the T_2 is burned and ~0.18 if all the T_2 is burned.

It can be seen that there are two main factors that can cause the fractional power in neutrons to be reduced: (1) operation at temperatures where the ratio of the reaction cross sections is minimized and (2) increasing the He^3-to-D ratio. This latter parameter cannot be pushed too far because eventually there would not be enough D atoms available for fusion with the He^3 and the fusion power density would be too low.

One example of how these two parameters can affect the power released in neutrons is shown in Fig. 2. Here is it shown that, independent of temperature, approximately 80% of the fusion power released in the DT reaction is in the form of neutrons. The neutron power fraction is ~50% for the DD reaction and, depending on the temperature and He^3-to-D ratio, as little as 1% of the power could be released in neutrons from D-He^3 plasmas.

Aside from the advantages of low neutron production, which will be covered later, the fact that 99% or so of the energy from this reaction is released in energetic charged particles also is of major significance. These particles can be converted to electricity

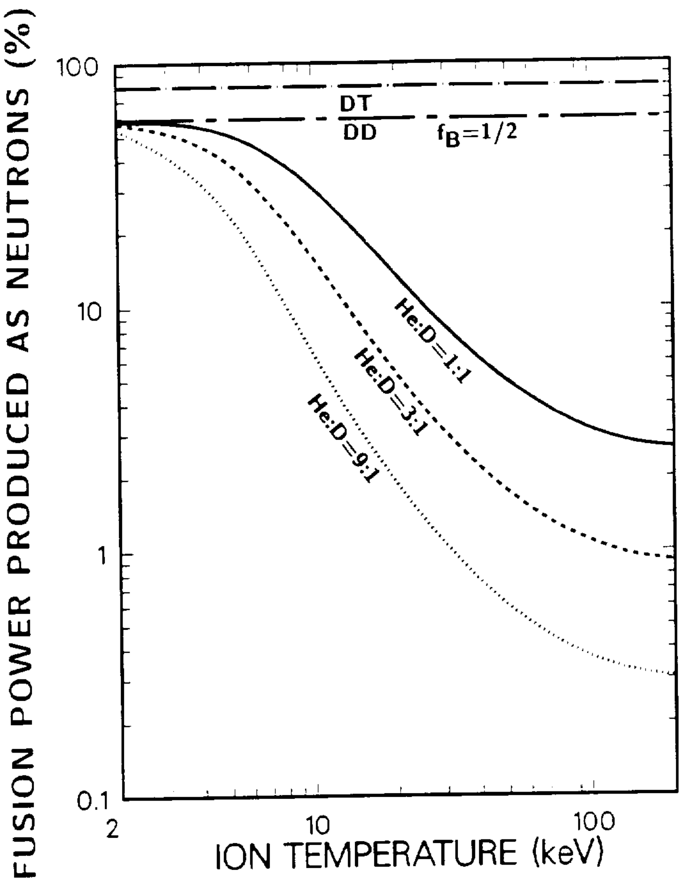


Fig. 2. Percent of fusion power in neutrons (50% tritium burnup).

via direct electrostatic means. Workers at LLNL in the U.S. have shown that this can be accomplished with 70-80% efficiency at lower energies (*Barr and Moir*, 1983). There is no reason to expect the higher energy (MeV) ions will substantially change those results.

Another advantage of this reaction is that it can be tailored to release large amounts of synchrotron radiation. Logan (unpublished data, 1986) has shown over half the energy from a D-He^3 plasma in a tokamak can be released in microwaves at ~3000 GHz (~0.1-mm wavelength). Such energy could be removed from the plasma chambers via waveguides and directed to useful areas outside the reactor. Direct conversion of the microwaves to electricity via rectennas could also improve the performance of the power plant. Other uses of the microwaves such as propagating energy over long distances in space or for local uses in the vacuum of space are also being investigated.

Returning to Figs. 1 and 2, it is evident that D-He^3 plasmas will have to be operated at temperatures about three times higher than DT power plants. Experiments at TFTR (*Strachan et al.*, 1989) have already achieved temperatures equivalent to ~20 keV and methods to get to 60-keV ion temperatures in tokamaks have already been discussed for the Next European Torus (NET) (*Emmert et al.*, 1989). Considering that in the past 2 decades the plasma temperatures in tokamaks have been increased by over a factor of 100, from 0.1 keV to 20 keV, it is not unreasonable to expect another factor of 3 increase in the next decade.

It is also of interest to note that when the actual amount of thermonuclear power that has been produced in the laboratory is examined, it is found that the situation is quite favorable for D-He^3. Figure 3 plots the power released from DD plasmas in magnetically confined devices since 1978 (no DT plasmas of any significance have been operated to date). It can be seen that starting with PLT in 1978 and progressing to TFTR in 1987, the DD fusion power released in the laboratory has increased to the level of almost 45 kW for a few seconds (D. Meade, personal communication, 1988). Recent experiments by *Jacquinot et al.* (1987) at JET had released over 9 kW from D-He^3 reactions and in 1988 reached the 50-kW level. It is anticipated that this energy release will be over 100 kW when all the heating is installed on JET in 1988.

How could the breakeven and ignition experiments for D-He^3 be conducted? *Emmert et al.* (1989) have shown that for the present European design of NET, simply inserting a D-He^3 plasma in place of the reference DT plasma could produce breakeven conditions. In fact, the energy multiplication can actually approach 2.5 if the inboard DT neutron shield is replaced with a thinner D-He^3 neutron shield (because of the lower neutron production, less material is needed to shield the magnets from radiation damage). Such a modification is easily achieved when the machine is constructed, and then the shield can be replaced before DT operation commences.

An even more interesting result was obtained by *Emmert et al.* (1987) when a combination of thinner inboard shields, a slightly more elongated plasma, and a 20% higher magnetic field on TF coils was examined. It was found that NET could actually ignite a D-He^3 plasma in this case and that significant power production (100 MW) could be achieved. Such modifications could be made for less than a 10% cost impact on the overall design and would allow scientists to study ignited D-He^3 plasmas in the 1999-2000 time period (assuming the 1993 construction start date is maintained). This is less than five years after it is hoped to reach ignited conditions in a DT plasma in CIT (*Schmidt et al.*, 1986). It is therefore quite possible that the scientific community could enter the twenty-first century with experience on ignited plasmas containing both D-He^3 and DT fuel.

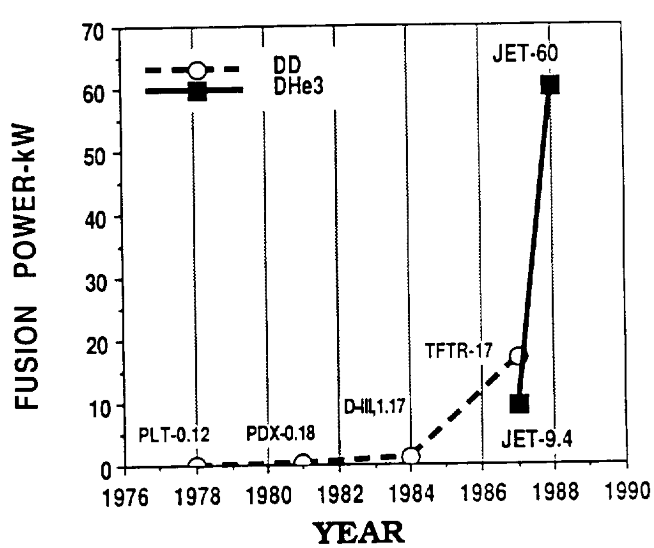


Fig. 3. Actual thermonuclear power produced in fusion devices.

In summary, the physics of the D-He^3 reaction are well established and, in fact, some D-He^3 experiments are being included in the research programs of the major tokamaks of the world today. One of the current reasons to study this reaction is to learn about the slowing down of fast ions in hot plasmas without activating the machine significantly with neutrons. This latter point is also one of the main reasons that scientists and engineers are interested in this fuel cycle from a commercial standpoint.

IMPACT OF D-He^3 FUEL CYCLE ON ELECTRIC POWER ISSUES

Assuming that a well-controlled, sustainable D-He^3 fusion plasma can be produced, what technological advantages would an electric power economy based on that fuel cycle have over one based on DT fusion or, in some cases, even a fission reactor economy? The areas where the D-He^3 fuel cycle can impact the major issues of concern to electric utilities of today are summarized in Table 1. These issues include radioactive wastes; inherent safety; increased availability and reliability; simplified maintenance; and cost. It can be seen from Table 1 that the main reason that the D-He^3 fuel cycle impacts these issues is because of the very low fraction of power in neutrons, as well as the greatly reduced radioactivity in the reaction by-products. Each of these issues will now be addressed primarily in the context of a DT fusion economy, but some observations will also be made with respect to a fission reactor economy.

Radioactive Wastes

It stands to reason that if fewer neutrons are produced per unit of power, then the amount of radioactivity induced in the structural material will also be reduced. The magnitude of this effect can be appreciated if one compares the structural radioactivity associated with the operation of two similar-sized tandem mirror reactors, one operating with a DT fuel (MINIMARS; *Lawrence Livermore National Laboratory,* 1986) and the other operating with a D-He^3 fuel (Ra; *Santarius et al.,* 1987). A comparison of the key operating parameters of MINIMARS and Ra is given in Table 2. It will be noticed that the total net power is the same (600 MWe) but the Ra reactor handles less thermal power to produce that electricity because of the predominance of charged particles and the extensive use of direct conversion in that cycle. Of course, the neutron wall loading is less by a factor of 66 in the Ra design.

Attaya et al. (1991) have calculated the waste disposal ratings (WDRs) from the two reactors and have shown how they would differ given realistic radiation damage lifetimes, as well as accounting for adequate magnet and personnel shielding. A summary of their results is given in Table 3 for three different structural materials: a low-activation austenitic steel like Tenelon, and a low-activation and a commercial ferritic steel like HT-9. Because the currently envisioned life of a structural component is only 15-20 MW-yr/m^2, the MINIMARS blanket must be changed approximately every 4-5 years and the average volume of compacted (100% dense) blanket waste discharged during operation is 3 m^3/yr or ~100 m^3 in total. The low neutron damage level (see section on availability and reliability) in the D-He^3 system means that the Ra first wall and shield (there is no blanket needed) will last the entire life of the reactor and still only accumulate less than 10% of the damage associated with the MINIMARS components when they are discharged. The only time that the radioactive structure needs to be changed in the Ra reactor is at the end of the plant life, and then the volume will be roughly half of the shield in a DT reactor.

TABLE 2. Key features of the DT MINIMARS and the D-He^3 Ra tandem mirror fusion reactors.

Parameter	MINIMARS	Ra
Fuel	DT	D-He^3
Net Electric Power (MWe)	600	600
n Wall Loading (MW/m^2	3.3	0.05
Fusion Power (MWt)	1231	1227
Total Thermal Power (MW) (including blanket multiplication)	1684	1237
Net Conversion Efficiency (%)	36	49

It is seen from Table 3 that the low activation structural wastes from a D-He^3 power plant qualify as Class A wastes when the plant is decommissioned. This means that instead of burying the wastes in a deep geologic repository (perhaps as much as a mile below the surface) as is now envisioned for fission reactor wastes, they could be disposed of in trenches near (within 1 m) the surface with no special requirements for containers. The shorter half life and relatively stable form of activated structure from a D-He^3 reactor should significantly reduce decommissioning costs and alleviate the public fear (however exaggerated) of sequestering wastes for thousands of years.

In contrast with the D-He^3 system, the wastes from a DT power plant, even if low-activation steels are used, can only qualify for Class C waste levels. These wastes have to be sequestered in stable form, at least 5 m from the surface, for 300 years.

Finally, if it were decided that present commercial ferritic alloys were the most economical and most radiation-damage-resistant structural materials, the use of the D-He^3 cycle would still permit surface land burial (Class C). This would not be the case for a

TABLE 1. Areas in which the D-He^3 fuel cycle can impact issues of major concern for the electric utility industry.

	Major Issues				
D-He^3 Fuel Characteristics*	Inherent Safety	Increased Availability	Simplified Maintenance	Radioactive Wastes	Cost
Reduced radioactivity	X	X	X	X	X
Reduced radiation damage	X	X	X	X	X
Direct conversion			X		X
Shorter path to commercialization					X

* Relative to DT fusion and fission.

TABLE 3. Waste disposal characteristics of structural materials used in DT and D-He^3 fusion reactor designs.

Structural Components*	DT Fuel MINIMARS	D-He^3 Fuel Ra
Neutron Wall Loading	3.3 MW/m^2	0.05 MW/m^2
Average Discharge (tonnes/yr)	24	0
Decommissioning (tonnes)	2560	1520
Low Activation Austenitic Alloy Tenelon	Class C	Class A
Low Activation Ferritic Alloy HT-9	Class C	Class A
Present-day Ferritic Alloy HT-9	Deep Geologic Waste Repository	Class C

* Compacted wastes, 10CFR61, 10-year decay before disposal.

Form of Waste: Class A—can be buried in shallow trench and no special requirements on stability of container. Waste may be unstable. Class C—Buried at least 5 m from the surface and in chemically and structurally stable container for 300 years. Deep Geologic Waste Repository—Must be sequestered from the public, at least 200 m below the surface, usually for periods exceeding several thousand years, and continuously monitored. Details considered on a case-by-case basis.

DT reactor and one would have to employ the deep geologic waste disposal sites for the structural material discharged from these reactors.

No matter how the subject of radioactive wastes is addressed, it is clear that from either an annual discharge volume, decommissioning volume, or surface vs. deep geologic burial, the D-He^3 cycle has significant advantages over a DT cycle. The contrast is even more evident when comparing the D-He^3 cycle to fission reactor wastes. The intangible effect of being able to avoid a centuries-long radioactive waste repository will be hard to quantify, but, as evidenced by the multibillion-dollar nuclear waste program in the U.S., it should have both political and financial benefits.

Inherent Safety

The safety of fusion power plants has been recently defined (*Holdren,* 1987) by the U.S. Department of Energy Committee on Environment, Safety, and Economic Aspects of Magnetic Fusion Energy (ESECOM) in terms of four levels of safety assurance (LSA):

Level 1: Inherent safety. Safety is assured by passive mechanisms of release limitation no matter what the accident sequence. The radioactive inventories and materials properties in such a reactor preclude a fatal release regardless of the reactor's condition.

Level 2: Large-scale passive protection. Natural heat transfer mechanisms suffice to keep temperatures below those needed—given radioactivity inventories and materials properties—to produce a fatal release unless large-scale geometry is badly distorted.

Level 3: Small-scale passive protection. Safety is assured by passive mechanisms of release limitations as long as severe violations of small-scale geometry—such as a large break in a major coolant pipe—are avoided, i.e., fatal release can only be assured if the coolant system is substantially intact.

Level 4: Active. There are credible initiative events that can only be prevented from escalating to a fatality—capable release by means of active safety systems.

On the basis of these definitions, current fission reactors are at level 4 and under some circumstances advanced LWRs (not yet built) could qualify at level 3. "Traditional" liquid metal cooled DT reactors also fall into levels 3 or 4. The D-He^3 fusion reactor qualifies for level 1 (inherently safe) according to the ESECOM report, even with a 1:1 D-to-He^3 ratio.

Calculations at Wisconsin, performed by *Sviatoslavsky* (1987) even before the ESECOM report, show that the consequences of a complete and instantaneous coolant loss are indeed minimal and that even a steel-structured D-He^3 power plant can qualify for LSA levels 1 or 2. The basis for this statement is that the temperature increase in the shield region would never reach levels required to volatilize radioactive isotopes in the structure. Sviatoslavsky found that even with absolutely no heat leak during the accident (i.e., as if a perfect thermal insulator were placed around the blanket immediately after losing all cooling water), the maximum temperature increase after one day is ~10°C for a D-He^3 ratio of 1:3 (see Fig. 4). After a week the temperature increase is only 50°C and after one month it would only increase by 200°C. Increasing the D-He^3 ratio to 1:1 only results in a 350°C increase after one month, again with no heat loss. It is obvious that a meltdown is virtually impossible in a D-He^3 reactor because of the low afterheat levels and because there always would be some heat leakage by conduction to the support structure or convection to the air in the building. Without the possibility of a major thermal excursion in the event of a highly unlikely, but theo-

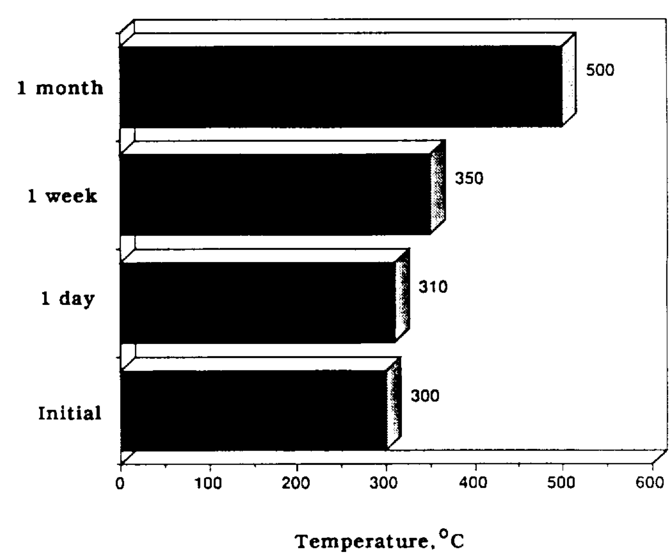


Fig. 4. Maximum temperature increase in a D-He^3 blanket.

retically feasible, accident, the safety regulations on such a plant should be eased and the label of "inherently safe" could be given to such a reactor.

Another area of interest is the loss of T from a fusion reactor in the event of an accident that could somehow destroy all containment. The worst case, of course, is to release all the T in the reactor in the form of tritiated water (HTO) and have the accident occur during the worst meteorological conditions. Assessing such an event for the MINIMARS plant (*Lawrence Livermore National Laboratory,* 1986), it was found that the maximum exposure to a member of the public who lives at the plant boundary from the entire 485 g T_2 inventory would be 24 Rem (coincidentally not far from the exposure that would have been experienced at a similar position to the Chernobyl plant during its accident). Because of the much lower T_2 content (2 g) in Ra (the T comes from one of the side DD reactions discussed in the section on the physics of the D-He^3 fusion reaction), the corresponding exposure to the public would be only 0.1 Rem, or roughly equivalent to the annual exposure of the natural background radiation (see Fig. 5). The lack of significant public exposure in the event of a catastrophic accident should be reflected in lower costs of construction and, hence, lower costs of electricity.

Availability and Reliability

There are several features of nuclear power facilities that generally have a negative impact on the reliability of the power plant and the fraction of time that it could be available for generating electricity. Four of these features are (1) radiation effects; (2) radioactivity; (3) necessity to insure that decay heat can be always removed; and (4) extremely stringent regulations on control equipment and the several levels of backup controls required to insure that no substantial release of radioactivity can occur.

The detrimental effect of radiation damage on mechanical properties causes designers to place very conservative operating limits on nuclear power plants. This can result in reduced temperatures, reduced pressures, and even premature replacement of components to be absolutely certain that there are no potential failures that could occur in the reactor.

In order to assess the difference between a D-He^3 cycle compared to DT fusion or fission reactors, it is neccesary to define a unit of damage that is meaningful to all systems. The materials community uses the dpa unit, which stands for displacements per atom, and is a measure of how many times a given atom is displaced during the metallic component's lifetime. A value of 10 dpa per year means every atom is displaced 10 times during 1 year of operation. It is possible for every atom to be displaced several times during the lifetime of a component because most of the displaced atoms simply and rapidly recombine with other vacant lattice positions. However, it takes only a small fraction of the displaced atoms to precipitate in the solid to produce damage and this is a function of the temperature of irradiation; usually the higher the temperature, the worse the effect.

To gain some perspective on the nature of this problem, it is instructive to use the Ra and MINIMARS reactor designs as reference points. It is known that after 30 FPY (full power years), the total DT damage to the first wall of MINIMARS is over 1100 dpa or every atom is displaced 1100 times. The materials community does not yet know how to make materials last for much over 150 dpa even in fission reactors, so the entire inner

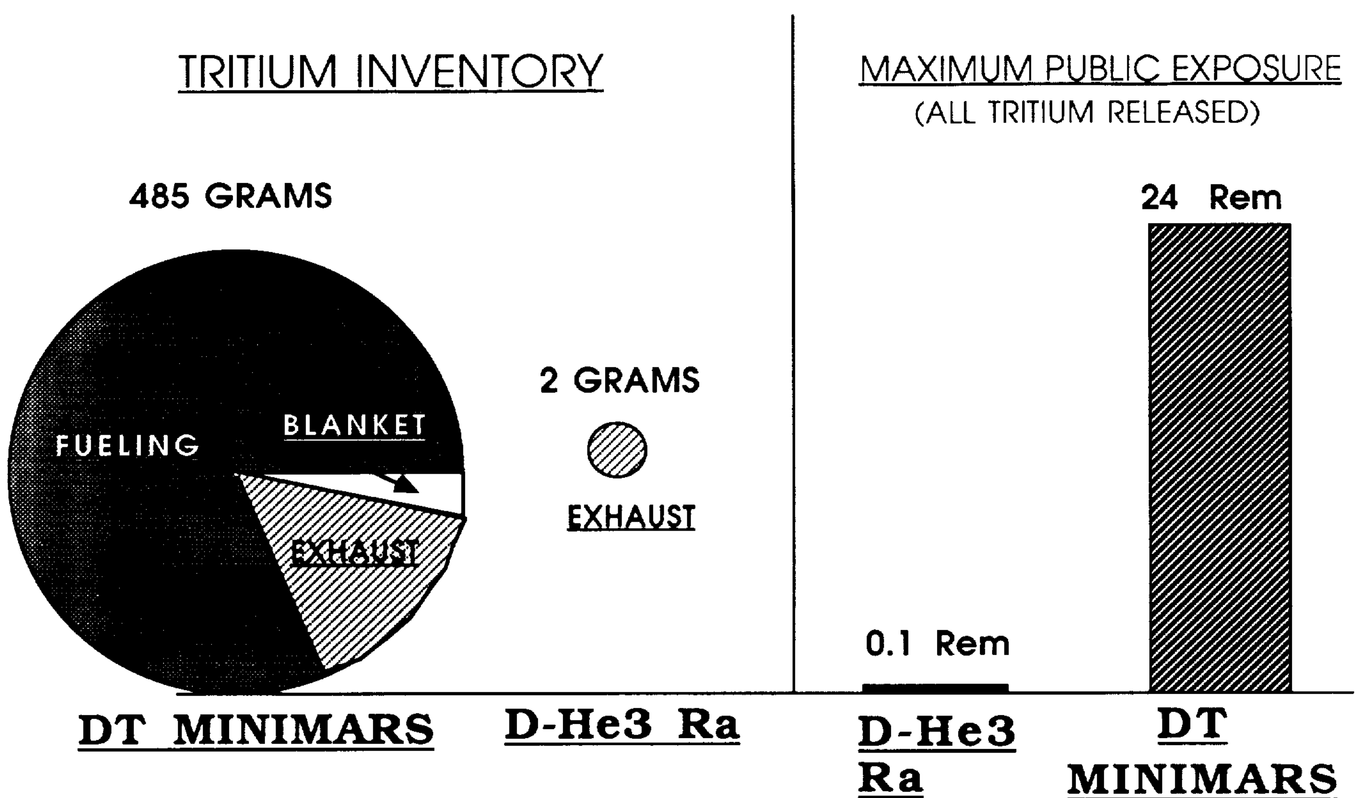


Fig. 5. Major safety differences between D-He^3 and DT-fueled 600-MWe reactors.

structure of the MINIMARS reactor must be replaced on the order of 5-10 times during the reactor lifetime. This causes loss of availability (higher electricity costs), as well as a larger volume of radioactive waste (see section on radioactive wastes).

On the other hand, it is found that in order to produce the same amount of electrical power, the components of the D-He^3 Ra reactor suffer only less than 20 dpa. Furthermore, since there is no need to run the blanket at very high temperatures to produce electricity efficiently, the operating temperature can be lower, thus expanding our choice of materials and confidence that they will last the life of the plant.

Figure 6 displays the dpa/temperature parameter space for Ra and MINIMARS along with an indication of the current data available on radiation damage to stainless steels from fission reactors. It is clear that the level of radiation damage produced in a DT reactor is much larger than anything that has been experienced in fission reactors. Contrary to that situation is the fact that both the radiation damage and temperature conditions are much lower for the D-He^3 power plant and it is easy to see why one expects that a reactor can be constructed that will last the lifetime of the plant. This single feature alone, i.e., no need to have scheduled replacement of reactor components should increase the availability of the plant by ~5% (2-3 weeks per year) over DT fusion or fission reactors (which periodically require refueling). The much more benign reactor environment should also help in reducing the risk of failure in the metallic components of the reactor making it more reliable and increasing our confidence in its safety.

The presence of radioactivity in the reactor as well as in the coolant system requires strict personnel access control and greatly hampers any component replacement or maintenance procedures. Simple tasks that take minutes in a nonnuclear system can take days in a nuclear plant. Furthermore, repairs seldom can be made to vital components while the plant is running for fear of promoting an accident that could release radioactivity. The above situation is familiar to those associated with fission reactors and the short-term (days) radiation levels in a DT facility are not much different than those in a fission reactor. As shown in the section on radioactive wastes, the total radioactivity associated with the D-He^3 cycle is ~20 to 80 times less than in a comparably sized DT plant so that the radiation levels should also be correspondingly lower. There is no way to quantify how this reduced radioactivity will affect the availability, but it should increase it if there is less T_2 to worry about and the radiation from the structure is down by more than an order of magnitude.

The necessity to protect against thermal excursions in the event of an accident has resulted in very complicated and expensive emergency core cooling systems (ECCS) on fission reactors. The associated instrumentation and the need to periodically test the system has a negative effect on both the reliability and availability

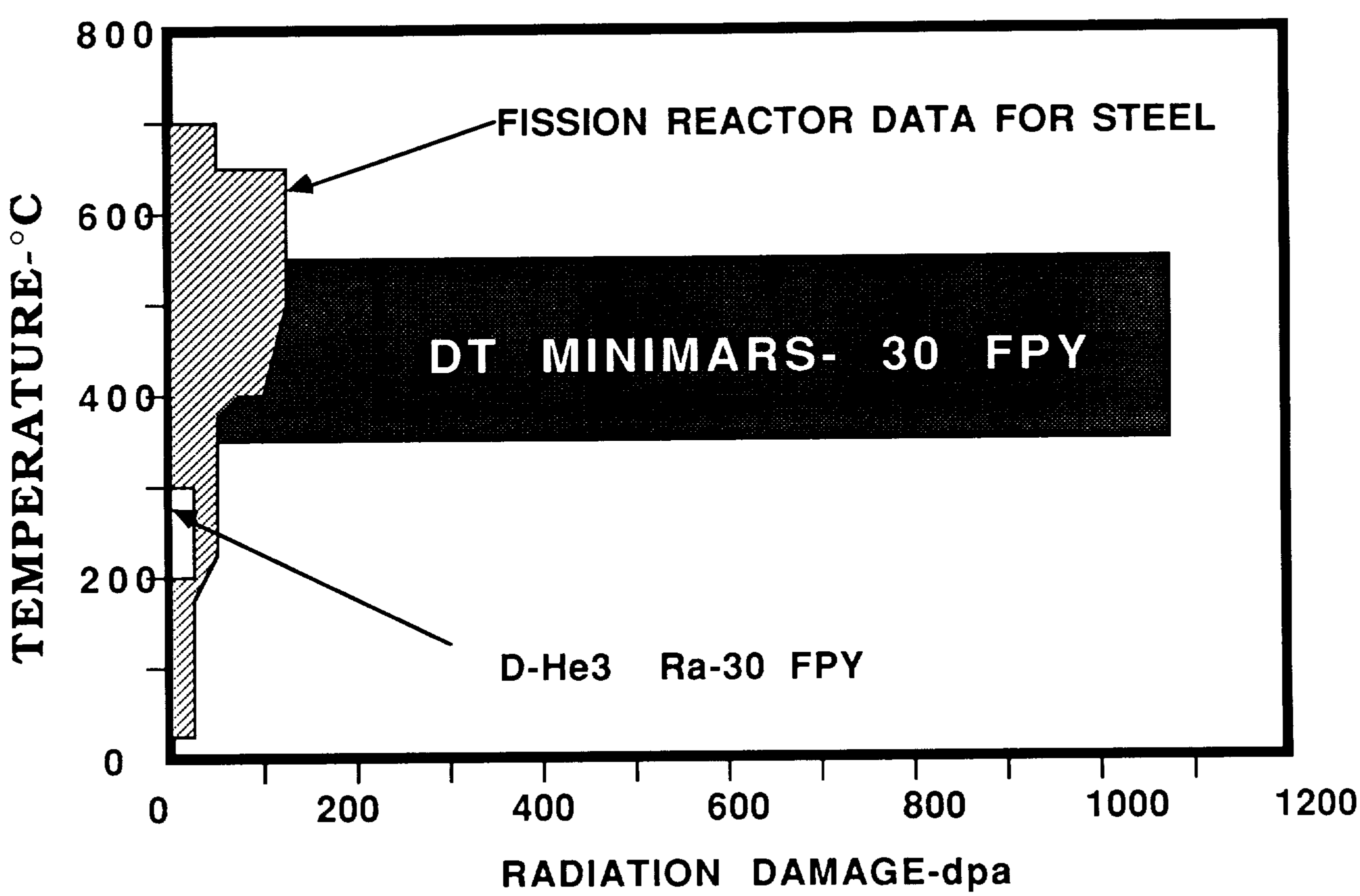


Fig. 6. Radiation damage in D-He^3 fusion reactors is much less than in DT systems.

of the reactor. DT fusion reactors will also require some form of cooling for specific components such as inboard magnetic shields in tokamaks, divertor plates, or limiters. However, the afterheat power densities are at least an order of magnitude less than in a fission reactor so that the time required to respond to an accident is correspondingly longer. This, coupled with the fact that the amount of harmful radioactivity that could be released in the event of a thermal excursion is lower, means that the emergency cooling system for a DT system can be less sophisticated.

On the other hand, the fact that a D-He^3 reactor does *not* need active cooling at all to prevent overheating means that fewer auxiliary systems and controls are required. This should mean that reliability is higher than in the DT reactor if all other systems are the same.

Finally, the need for several levels of containment to prevent a fatal release of radiation from fission reactors currently requires complex, costly, and sensitive control equipment having nothing to do with the primary function of generating electricity. The random failure of this equipment and the need to shut down the plant while it is being replaced is a current nuisance for some fission reactors in the U.S. Similar, although somewhat less sophisticated, equipment would be needed to guard against T_2 release from a DT power plant. However, the extremely low inventory of volatile radioisotopes (e.g., only a few grams of T_2) in a D-He^3 power plant should greatly relieve its operators from such complex and in-depth containment structures with corresponding increase in reliability of the reactor.

It is clear from the above discussion that the general lack of radiation damage, the low T_2 inventory, the lack of a need for an ECCS, and the much reduced containment requirements for a D-He^3 reactor should lead to a more reliable fusion power plant. This should also carry over to the availability for D-He^3 vs. DT reactors. Because fusion power plants may, in general, be more complicated than fission plants from a control standpoint, it is too soon to speculate on a quantitative advantage for fusion vs. fission.

Maintenance

It is difficult to speculate at this time on the degree of maintainability of a D-He^3 fusion power plant vs. fission reactors. Since fusion and fission reactors are so different in size, components, and environment (e.g., magnets, cryogenics, vacuum equipment, etc.), it is pointless to attempt any quantitative comparison until a fusion power plant is built. Nevertheless, if one compares DT vs. D-He^3 fusion reactors, one would be tempted to believe that the 1 to 2 order of magnitude reduction in radioactivity in the He^3 system should make it easier to maintain vital equipment. The lack of a need for any liquid metals in a D-He^3 system should also reduce the time necessary to get a coolant system ready for repairs. Finally, the fact that most of the energy could be converted to electricity with static equipment (as opposed to rotating equipment) and the large heat exchangers/pumps associated with a Rankine cycle should mean fewer failures and less need for maintenance.

It is probably safe to say that the maintainability of a D-He^3 fusion reactor is qualitatively better than a DT reactor but any speculation on fusion vs. fission is premature at this time.

Cost

It is obviously too early to calculate the absolute cost of electricity from any fusion power plant. However, the *relative* costs of the DT and D-He^3 fusion cycles can be compared with some confidence. The MARS (*Lawrence Livermore National Laboratory*, 1984), Ra (*Santarius et al.*, 1987) (1200 MWe version), and STARFIRE (*Baker et al.*, 1980) reactors serve to illustrate the advantages that lower neutron production and increased conversion efficiency can have. Using the same costing algorithms from the MARS and the MINIMARS studies, as well as other algorithms derived from the U.S. commercial tokamak reactor study program, a detailed cost breakdown of these systems is given in Table 4. The costs are given in 1986 dollars and are for a mature industry (i.e., not the first plant ordered).

The first part of Table 4 gives a brief summary of the operating conditions for both the tokamak (STARFIRE) and tandem mirrors (MARS and MINIMARS) reactors. All the plants are normalized to 1200 MWe and the same availabilities and construction times are assumed. The two major differences are the (1) much lower neutron wall loading in Ra (0.05 MW/m^2 vs. ~3-4 MW/m^2 in MARS, MINIMARS, and STARFIRE) and (2) much higher conversion efficiency to electricity for the D-He^3 Ra reactor (60% vs. 34-49% for the DT systems).

Because the charged particles can be directly converted to electricity with 80% or higher efficiencies, one can generate electricity from D-He^3 fusion reactors at roughly twice the efficiency from fossil or fission power plants (see Fig. 7). The DT and DD systems have only 20% and 50% respectively of their energy released in charged particles and therefore have lower overall efficiencies than for the D-He^3 case. However, the fusion systems are generally higher than the thermodynamically limited systems used in light water fission reactors (LWFRs) and fossil plants. The higher efficiency can significantly decrease the cost of electricity and has the additional benefit of reducing the size of the heat transport system, the turbine buildings, and the waste heat facilities, as shall be seen in the following analysis.

Some of the more striking observations that can be made from Table 4 are

1. The direct capital cost of a D-He^3 fusion reactor could be one-half that of DT tokamaks or DT tandem mirrors.

2. Building costs of a D-He^3 plant can be reduced because of the lower radioactivity and volatile T_2 inventory.

3. The lack of a T_2 breeding blanket and reduced magnet shielding in a D-He^3 system can greatly reduce the reactor internal cost.

4. The magnet costs of Ra are reduced over MARS because of the different end-cell physics configuration.

5. The extensive use of direct conversion results in a greatly reduced heat transport system, as well as much smaller turbine and electric plant costs.

6. Without adding in the fuel costs, the COE from the 1200-MWe Ra reactor is ~40% of the DT systems studied.

The question of He^3 fuel costs can now be addressed in a parametric fashion. Figure 8 shows how the COE in Ra varies with the cost of He^3. It can be seen that the COE increases approximately 1 ml per kWhr for every additional ~\$80/g one is willing to pay for the fuel. It can be seen that the crossover point between DT and D-He^3 systems is at ~\$2500-3500/g (or 2.5 to 3.5 billion dollars per tonne). Even though the COEs would be similar at that level, society would still reap the benefit of lower thermal pollution, much less radioactive waste, no need for deep geologic burial (or even Class C in some cases), greater safety assurances, and better reliability and higher availability. While the exact numbers should not be overemphasized at this time, the possibility of buying He^3 at several billion dollars (or more) per tonne should provide sufficient economic incentive to aggressively develop a commercial market for this fuel.

TABLE 4. Cost comparisons between DT and D-He^3 fusion reactor designs.

Key Parameters	STARFIRE	MARS	MINIMARS	Ra
Reactor Type	Tokamak	Mirror	Mirror	Mirror
Fuel	DT	DT	DT	D-He^3
Net Electrical Power (MWe)	1200	1200	1200	1200
Fusion Power (MW)	3510	2600	2295	2008
n Wall Loading (MW/m^2)	3.6	4.3	4.5	0.05
Net Conversion Efficiency (%)	30	42	38	60
Availability (%)	75	75	75	75
Construction and Licensing Time (yr)	6	6	6	6
Costs $M (1986$)				
Land	5	5	5	5
Building and Site	527	280	228	145
Reactor				
Internals	488	233	209	138
Magnets	261	558	107	180
Heating	55	113	158	106
Power Conditioning	89	96	†	181
Heat Transfer	138	457	138	34
Fueling	70	64	72	31
Instr. and Control	36	28	22	25
Maintenance Equipment	58	29	28	40
Turbine Plant	312	308	220	76
Electric Plant	178	179	81	91
Heat Transfer	67	9	32	16
Miscellaneous	62	37	41	36
Direct Costs (M$)	2345	2397	1342	1110
Total Capital Costs (M$)	3648	3658	2043	1690
O & M Costs (M$)	30	22	19	23
Repl. and Fuel (M$)	26	9	24	0
Capital Costs ($M/kWhr)	3040	3048	1702	1408
Total Cost ($M/kWhr)	53	52	28	21*

* Fuel costs extra.
† Included in other accounts.

Data from *Kulcinski et al.* (1987).

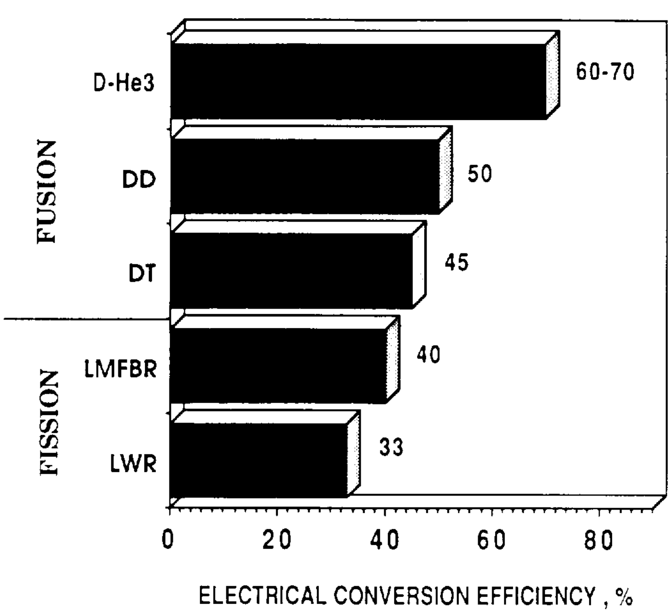


Fig. 7. Comparison of nuclear energy electrical conversion efficiencies.

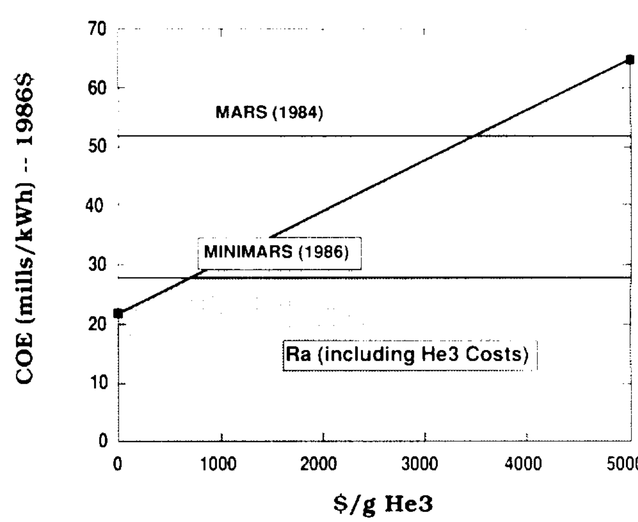


Fig. 8. Effect of He^3 costs on cost of electricity from fusion plants (1200-MWe versions).

Path to Commercialization

One of the great advantages of the D-He^3 fuel cycle is the fact that once it can be ignited, the development path to a commercial unit should be much easier than for the DT system. After ignition of a DT plasma is achieved and the understanding of how to control such plasmas is in hand, there remains the long and expensive process of testing materials and breeding concepts for commercial units. For example, as shown in Fig. 6, the full lifetime exposure of a typical DT fusion first wall is over 1000 dpa. While it is not anticipated that the materials community would ever expect to develop a material that would last that long, economics dictate that the first wall life be at least ~10-15 MW-yr/m^2 (130-200 dpa). It is current engineering practice to extrapolate no more than a factor of ~3 from well-documented data in order to commit to building a facility. This would imply that data in the 40-70-dpa range from 14-MeV neutrons would be required. To date, the highest 14-MeV neutron exposure to any metal is less than 0.1 dpa and dramatically illustrates why materials test facilities will be needed for the DT system. In addition to materials test facilities, demonstration power plants would have to be built to integrate the plasma physics and materials physics aspects. The current U.S. approach to that process is shown in Fig. 9.

On the DT side it begins with the CIT (*Schmidt et al.,* 1986) device scheduled for operation in the early 1990s. The main objective of this device is to demonstrate ignition of DT plasmas, presumably about the middle of the 1990s.

Plans to build an engineering test facility that would follow the CIT project are already underway in several countries (*Abdou et al.,* 1986). Using the generic name of an engineering test reactor (ETR) for this device, it can be seen that current plans call for construction in 1993 and operation in the late 1990s. This test facility would expand upon the DT ignition physics learned from CIT and do a limited amount of materials and blanket component testing. Presently, it is anticipated that the testing phase would last about 12 years and accumulate ~30 dpa in test modules. No electricity would be produced by this device (except possibly from small test blankets that could be inserted into the side of the reactor).

The ETR would be followed by a demonstration plant (Demo) that would integrate the plasma, materials, and full T breeding blankets into one power-producing facility. This Demo is expected to produce electricity, but not on a regular—and certainly not on an economical—basis. Finally, if all went well, a commercial facility would be built sequentially to the Demo, hopefully to be ordered by an electric utility. The total time from now until the first operation of this DT commercial unit could be 50 years or more.

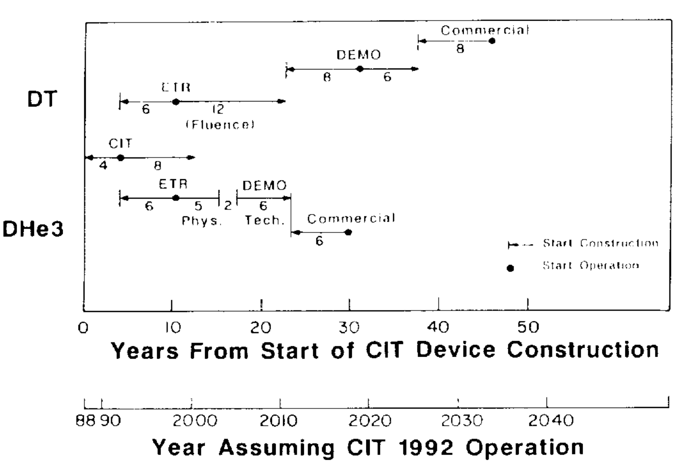


Fig. 9. Development scenarios for fusion.

On the other hand, if the experiments with the D-He^3 cycle in the ETR facility were to be successful, then an alternative schedule could be pursued. Since the D-He^3 fuel cycle causes much less induced radioactivity, it should be possible to convert the ETR unit directly into a power-producing Demo. This is possible because, with the low neutron damage level associated with the D-He^3 cycle, one does not need a long testing program for materials, and because there is no need to breed T, one does not need to test blanket concepts. Moving directly to a Demo on the same site by adding direct conversion and power generation equipment saves both time and capital investment. If the Demo can be successfully operated in an electricity producing mode for four to five years, the engineering community would then be ready to move on to a commercial unit. The overall time savings could be between 10 and 20 years compared to the DT case and it is possibly the only way to have commercial fusion power reactors by the year 2020. This time period is important, as shall be seen later, because it determines when one would begin to require He^3 from nonterrestrial sources.

WHAT ABOUT He^3 RESOURCES FOR NEAR-TERM RESEARCH?

Thus far the question of fueling the near-term test reactors until a larger external source of He^3 fuel for commercial operation can be obtained has not been addressed. The answer lies with the terrestrial resources of He^3, which fall into two categories as shown in Table 5 (*Wittenberg et al.,* 1986). The first has to do with the primordial He^3 present in the Earth at its creation. Unfortunately, most of that He^3 has long since diffused from the Earth and been lost through the atmosphere to outer space. What is left in any retrievable form is contained in the underground natural gas reserves. Table 5 shows that the underground U.S. strategic He storage caverns contain some 30 kg of He^3. If one were to process the entire U.S. resource of natural gas, another 200 kg might be obtained, but the cost and side effects of such a project make it very unlikely that we could do such a thing.

Another source of He^3 on Earth is from the decay of T ($t_{1/2}$ = 12.3 yr). When T decays, it produces a He^3 atom and a β particle. Simple calculations of the inventory of T in the U.S. thermonuclear weapons show that if the He^3 were collected, some 300 kg would be available by the year 2000. Presumably about the same amount of He^3 would be available from the weapons stockpile of the U.S.S.R. The equilibrium production of He^3 (assuming no future change in weapons stockpiles) is around 15 kg per year in each country. It may seem strange to rely on a by-product from weapons for a civilian application, but He^3 is commercially available today from just such a process. One can purchase up to 1.38 kg of He^3 per year directly from the U.S. government (10,000 l at STP), all of which comes from T decay. Obviously, considerably more is available and simple calculations of the T production from U.S. facilities at Savannah River indicate that T production is in the 10-20 kg/yr range. This would imply an "equilibrium" He^3 production rate of ~10-20 kg/yr minus losses in processing.

TABLE 5. Reserves of He^3 that could be available in the year 2000.

Source	Cumulative Amount (kg)	Production Rate after Year 2000 (kg/yr)
Primordial-Earth		
• U.S. helium storage	29	—
• U.S. natural gas storage	187	—
Tritium Decay		
• U.S. nuclear weapons	300	~15
• CANDU reactors	10	~12
Total	>500	~17

Note: 1 kg of He^3 burned with 0.67 kg of D yields 19 MW-yr of energy.

One could also get smaller amounts of He^3 from the T produced in the heavy water coolants of Canadian CANDU reactors. This could amount to 10 kg of He^3 by the year 2000 and He^3 will continue to be generated at a rate of ~2 kg per year thereafter.

It should be noted again that 1 kg of He^3, when burned with 0.67 kg of D, produces approximately 19 MW-yr of energy. This means that by the turn of the century, when there could be several hundred kilograms of He^3 at our disposal, the potential exists for several thousand MW-yr of power production. The equilibrium generation rate from T resources alone could fuel a 300-MWe plant indefinitely if it were run 50% of the time.

Clearly, there is enough He^3 to build an ETR (few hundred megawatts running 10-20% of a year) and a demonstration power plant of hundreds of megawatts run for many years. This could be done without ever having to leave the Earth for fuel. The real problem would come when the first large (GWe) commercial plants could be built, around the year 2020. The next major question is whether one can get the He^3 fuel from the Moon on a timescale consistent with our development path.

WHAT AND WHERE ARE THE He^3 RESOURCES ON THE MOON?

Wittenberg et al. (1986) were the first to publish their discovery of He^3 in the regoliths on the Moon. Since that time, work by the Wisconsin group has elaborated on the original idea. A few highlights will be summarized here.

The origin of the main source of lunar He^3 is the solar wind. Using data that showed that the solar wind contains ~4% He atoms and that the He^3/He^4 ratio is ~480 appm, it was calculated that the surface of the Moon was bombarded with over 250 million metric tonnes in 4 b.y. Furthermore, because the energy of the solar wind is low (~3 keV for the He^3 ions), the ions did not penetrate very far into the surface of the regolith particles (0.1 μm). The fact that the surface of the Moon is periodically tilled as the result of frequent meteorite impacts results in the He being trapped in soil particles to depths of several meters.

Analysis of Apollo and Luna regolith samples revealed that the total He content in the Moon minerals ranges from a few to 70 wtppm (see Fig. 10) (*Cameron,* 1987). The higher concentrations are associated with the regolith on basaltic maria of the Moon and the lower contents associated with the highland rocks and basin ejecta. Clearly the higher concentrations are in the most accessible and minable material. Using the data available, it is calculated that roughly a million metric tonnes of He^3 are still trapped in the surface of the Moon (*Wittenberg et al.,* 1986) (see Table 6).

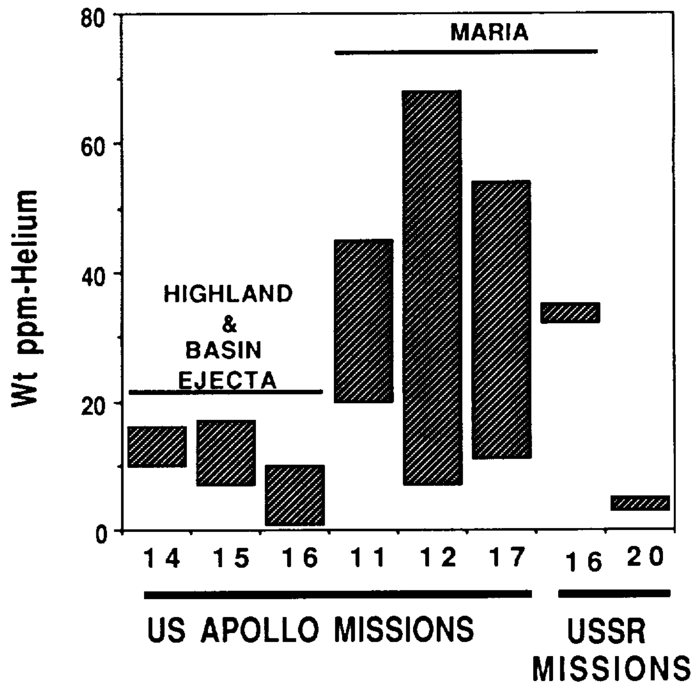


Fig. 10. Measured He content in lunar samples.

TABLE 6. He^3 content of lunar regolith.

Location	% Lunar Surface	Average He Concentration (wtppm)	Tonnes He^3
Maria	20	30	600,000
Highlands and Basin Ejecta	80	7	500,000
Total			1,100,000

The next step is to determine the most favorable location for extracting this fuel. *Cameron* (1987) has shown (Fig. 11) that there is an apparent association between the He and TiO_2 content in the samples. Assuming that this is generally true, he then examined the data on spectral reflectance and spectroscopy of the Moon, which showed that the Sea of Tranquillity (confirmed by Apollo 11 samples) and certain parts of the Oceanus Procellarium were particularly rich in TiO_2. It was then determined, on the basis of the large area (190,000 km^2) and past U.S. experience, that the Sea of Tranquillity would be the prime target for initial investigations of lunar mining sites. This one area alone appears to contain more than 8000 tonnes of He^3 to a depth of 2 m. A backup target is the TiO_2-rich basalt regolith in the vicinity of Mare Serenitatis sampled during Apollo 17 (*Schmitt,* 1973).

HOW WOULD THE He^3 BE EXTRACTED?

Since the solar wind gases are weakly bound in the lunar regolith, it should be relatively easy to extract them. *Pepin et al.* (1970) found that heating lunar regolith caused the He^3 to be evolved above 200°C, and by 600°C, 75% of the He gas could be removed (Fig. 12).

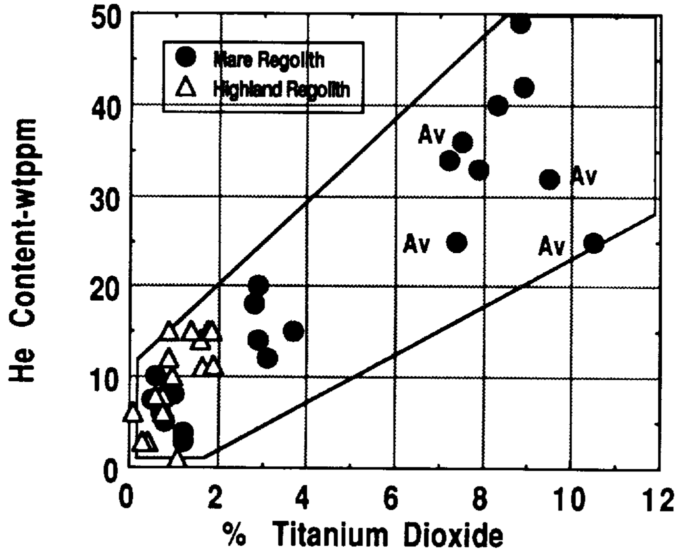


Fig. 11. Relationship between He content and TiO_2 in lunar regolith.

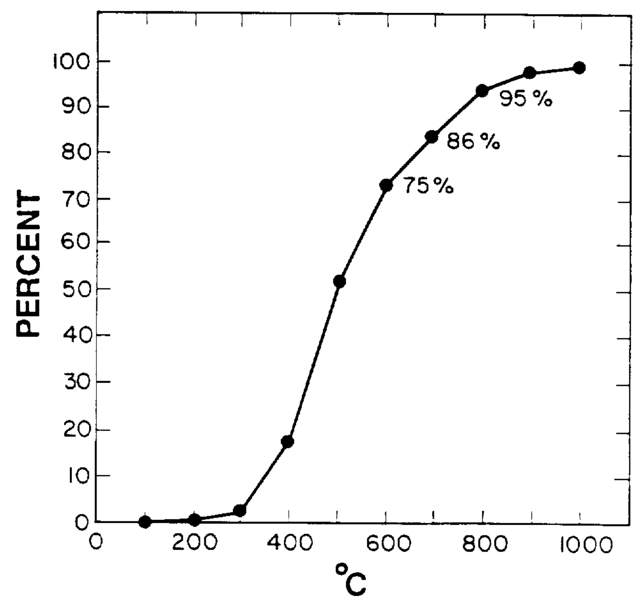


Fig. 12. He^3 evolution from lunar soil. Data from *Pepin et al.* (1970).

There are several methods by which the He could be extracted and a schematic of one approach is shown in Fig. 13 (*Sviatoslavsky*, 1988). In this unit, the loose regolith, to a depth of 60 cm, is scooped into the front of the robotic unit. It is then sized to particles less than 100 μm in diameter because there seems to be a higher concentration of solar gases in the smaller particles (presumably because of the high surface-to-volume ratio). After beneficiation, the concentrate is preheated by heat pipes and then fed into a solar-heated retort. At this point it is anticipated that heating to only 600 or 700°C is required and the volatiles (H_2, He^4, He^3, C compounds, and N_2) are collected with the spent concentrate being discharged through heat pipes to recover 90% of its heat. The concentrate is finally dropped off the back of the moving miner. Note that in the one-sixth-g environment relatively little energy is expended lifting material.

Of course, this scheme would only work during the lunar day, but orbiting mirrors, nuclear reactor heat from a mobile power plant, or indirect heating from microwaves generated at a central power plant on the Moon could extend the operating time. Alternative schemes are being examined through parametric analyses of such variables as particle size vs. temperature vs. yield, mining depth vs. He^3 concentration vs. particle size distribution, manned operation vs. robotic operations vs. maintenance costs, mechanical particle separation vs. gaseous particle separation vs. yield, solar vs. nuclear power, etc.

Once the volatiles are extracted, they can be separated from the He by isolation from the lunar surface and exposure to outer space (<5 K) during the lunar night. Everything except the He will condense and the He^3 can be later separated from the He^4 by superleak techniques well established in industry (*Wilkes*, 1978).

For every tonne of He^3 produced, some 3300 tonnes of He^4, 500 tonnes of N, over 400 tonnes of CO and CO_2, and 6100 tonnes of H_2 gas are produced (see Fig. 14). The H_2 will be extremely beneficial on the Moon for lunar inhabitants to make water and for propellants. Transportation of that much H_2 to the Moon, even at $1000/kg (less than one-half of present launch costs), would cost ~6 million dollars. As previously noted, the He^3 itself could be worth as much as ~1 billion dollars per tonne. Of the other volatiles, the N_2 could also be used for plant growth, the C for manufacturing or atmosphere control, and the He^4 for pressurization and as a power plant working fluid.

HOW MUCH IS THE He^3 WORTH?

While it is hard to anticipate the cost of energy in the future, one can extrapolate these costs based on today's experience. First of all, it is worthwhile to get a feeling for how much energy is contained in the He^3 on the Moon. If the resource is 1 million metric tonnes, then there is some 20,000 TW-yr of potential thermal energy on the Moon. This is over 10 times more energy than that contained in economically recoverable fossil fuels on Earth. This amount of energy is also 100 times the energy available from economically recoverable U on Earth burned in LWRs on a once-through fuel cycle, or roughly twice the energy available from U used in LMFBRs.

The second point to note is that only 25 tonnes of He^3, burned with D in Ra-type reactors, would have provided the entire U.S. electrical consumption in 1986 (some 285 GWe-yr). The 25 tonnes of condensed He^3 could fit in the cargo bay of a spacecraft roughly the size of the U.S. shuttle.

A third point of interest is that in 1986 the U.S. spent over 40 billion dollars for fuel (coal, oil, gas, uranium) to generate electricity. This does not include plant or distribution costs, just the expenditure for fuel. If the 25 tonnes of He^3 just replaced that fuel cost (and the plant costs and distribution costs stayed the same), then the He^3 would be worth approximately 2 billion dollars per tonne. At that rate, it is the only thing we know of on the Moon that is economically worth bringing back to Earth

An obvious question at this point is how much does it cost to obtain He^3 from the Moon? The answer depends on three things: (1) Will the U.S. develop a Moon base for scientific or other mining operations without the incentive of obtaining He^3?

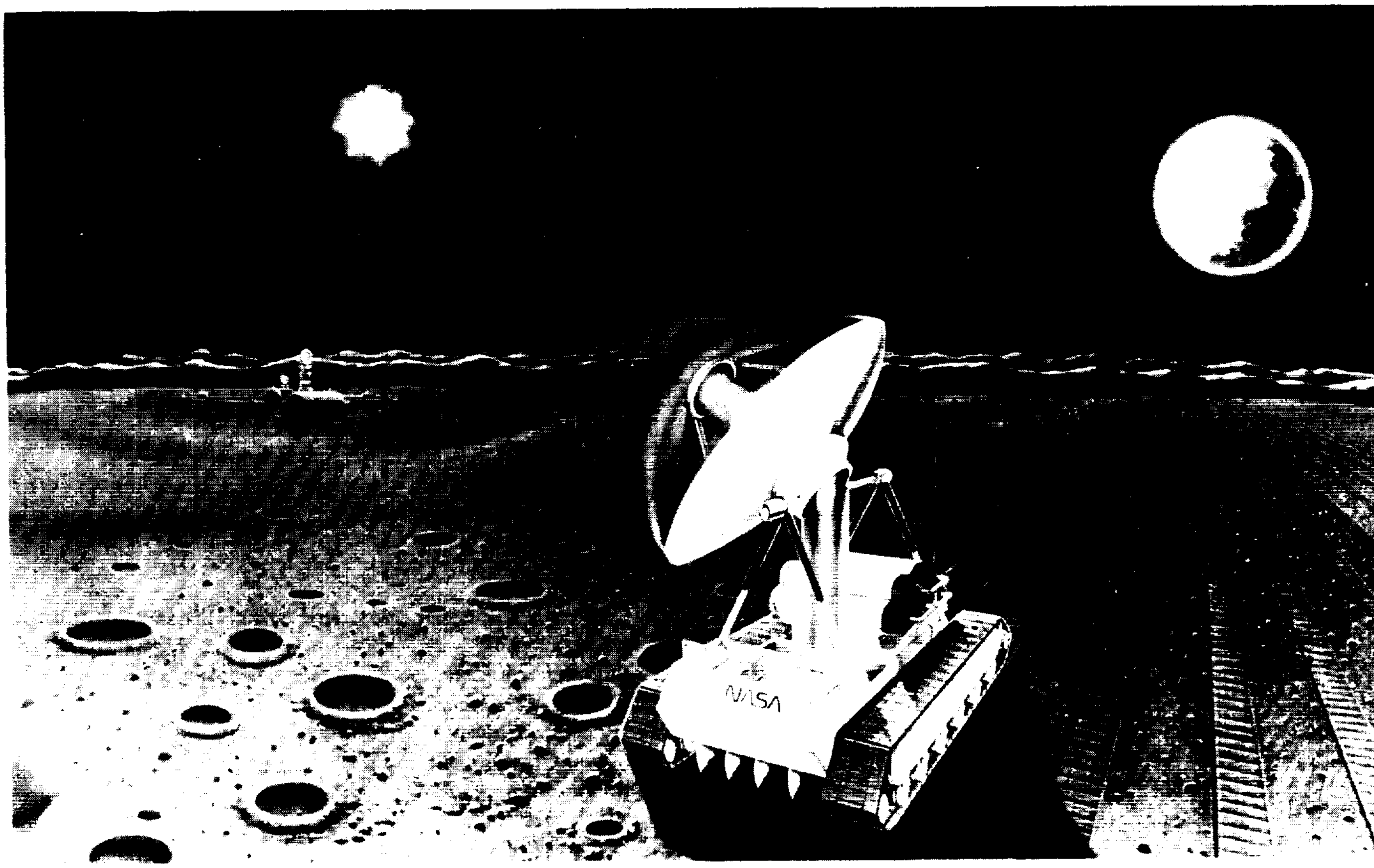


Fig. 13. Design of lunar vehicle to extract He³ from regolith using direct solar radiation.

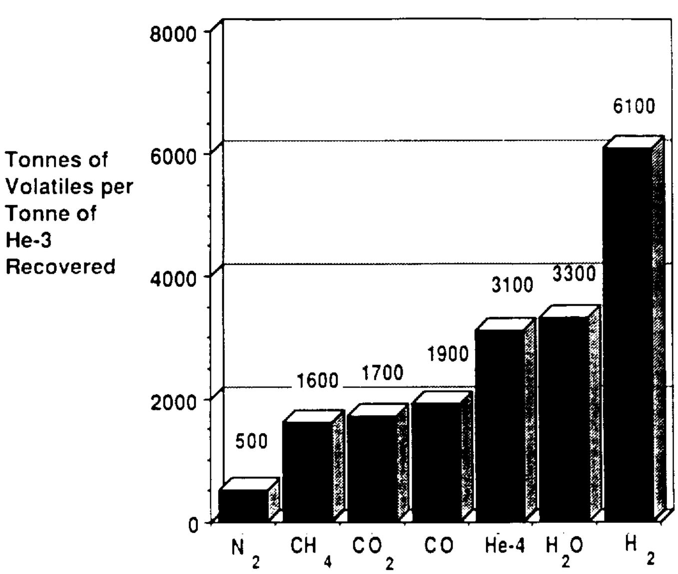


Fig. 14. By-products of lunar He³ mining.

(2) If the answer to the preceding question is yes, then how much will the *incremental* costs of mining He³ be after manned lunar bases are already in place? (3) How will the benefits of the side products be treated? For example, will one be able to "charge" the lunar colony for the H_2, N_2, He, or C compounds extracted from the lunar regolith?

The answer to question (1) is probably yes. In a report to NASA by *Ride* (1987), it was stated that one of the four major programs in NASA should be a return to the Moon and the establishment of a manned base early in the twenty-first century. This recommendation was made without any reference to the He³ mining possibilities. At this time it appears reasonable to assume that the cost of returning to the Moon will be borne by the U.S. government as a general investment in science.

The answer to question (2) cannot be given at this time, but should be the subject of study in the near future. It appears, based on the mobile mining concept described earlier, that the equipment could be transported to the Moon for well under a billion dollars (e.g., at $1000/kg this would allow 1000 tonnes to be transported to the Moon). Operational costs should be well under a billion dollars per year even if everything has to be transported to the Moon and no use of lunar materials is allowed.

The possibilities of "selling" the by-products of the He^3 to lunar colonies is very intriguing. The by-products from mining just 1 tonne of He^3 would support the annual lunar needs of 1400 people for N_2 (food and atmosphere), 22,000 people for CO_2 used to grow food, and 45,000 people for H_2O. If the cost of transporting the equipment to extract these volatiles from the lunar regolith is written off against the savings in sending up life support elements such as H_2, N_2, or C for manned lunar bases, then it is possible that the cost of He^3 may in fact be negligible. If that were true, then the COE from D-He^3 fusion power plants would indeed be much cheaper than from DT systems (see Fig. 8 and Table 2) and possibly even from fission reactors (without taking credit for all the environmental advantages of this fuel cycle).

To answer the question posed by the title of this section, it is our opinion that a realistic figure for the worth of He^3 on the Earth is ~1 billion dollars per tonne. This would still allow D-He^3 fusion plants to be competitive with DT systems and provide adequate incentive for commercial retrieval from the Moon.

IS THE TIMETABLE REALISTIC?

It was shown in the section on the impact of the D-He^3 fuel cycle on electric power issues that no He^3 would probably be required from the Moon before 2015. A recent study by *Sviatoslavsky* (1988), using conservative U.S. energy growth rates (2%) and conservative penetration rates of fusion beginning with the first plant in 2015, resulted in the He^3 demand curve shown in Fig. 15. This demand results in the cumulative He^3 requirements shown in Fig. 16. It can be seen that the demand reaches the ~1 tonne per year level in 2030, 10 tonnes per year in 2032, and by 2050, a cumulative total of nearly 200 tonnes of He^3 could be required.

This schedule should be compared to future activities in space proposed by the recent National Commission on Space (NCOS) report (1986) shown in Fig. 17. This plan envisions the first lunar base to be established by 2005 with the first pilot plant production of oxygen by 2010. By 2015 it is anticipated that some *500* tonnes of oxygen per year could be exported from the Moon to the space station (compare this to 1 tonne of He^3 per year required a decade later). Furthermore, the extraction of oxygen has to be done at 1300°C, a much more difficult job than working at 700°C for He^3.

Therefore, it seems that the schedule and technology requirements required to extract He^3 from the Moon are consistent with current proposals to procure oxygen for the space station or to place a manufacturing colony on the Moon.

CONCLUSIONS

It is shown in this paper that the D-He^3 fusion fuel cycle is not only credible from a physics standpoint, but that its breakeven and ignition characteristics could be developed on roughly the same time schedule as the DT cycle. It was also shown that the extremely low fraction of power in neturons, the lack of significant radioactivity in the reactants, and the potential for very high conversion efficiencies, can result in definite advantages for the D-He^3 cycle with respect to DT fusion and fission reactors in the twenty-first century.

More specifically, the D-He^3 cycle can

1. Eliminate the need for deep geologic waste burial facilities and the wastes can qualify for Class A, near-surface land burial;

2. Allow "inherently safe" reactors to be built that, under the worst conceivable accident, cannot cause a civilian fatality or result in a significant (>100 mrem) exposure to a member of the public;

3. Reduce the radiation damage levels to a point where no scheduled replacement of reactor structural components is required, i.e., full reactor lifetimes (~30 FPY) can be credibly claimed;

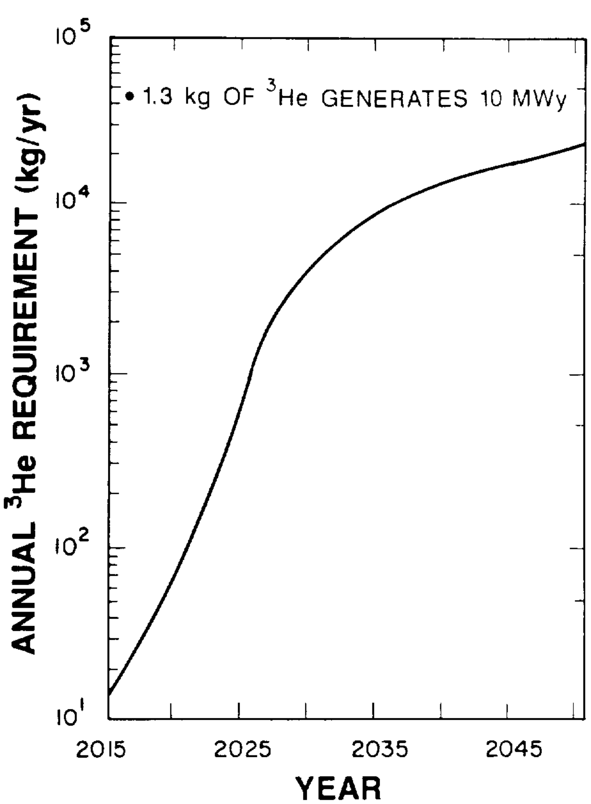


Fig. 15. He^3 demand curve.

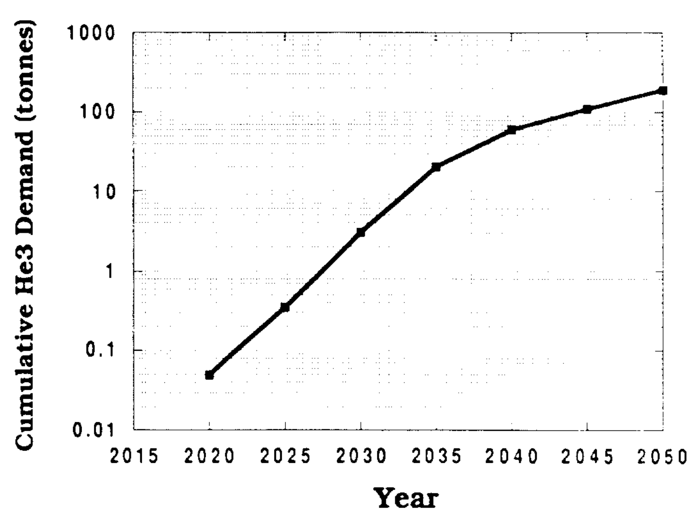


Fig. 16. Projected utility requirement for He^3 fuel.

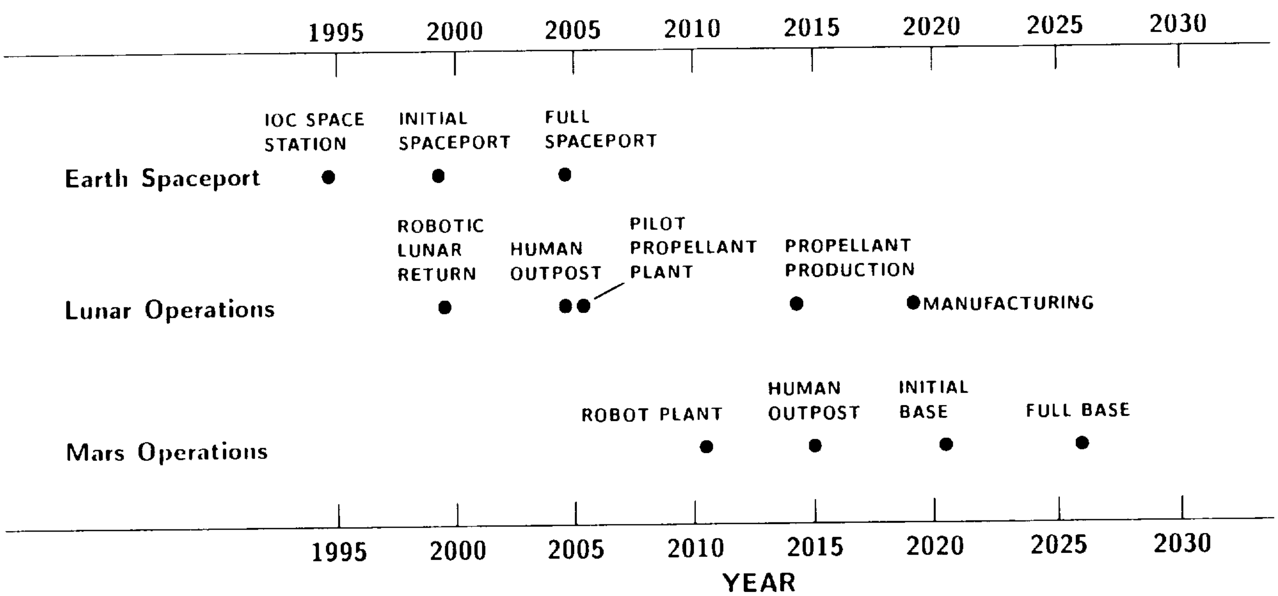


Fig. 17. Present plans for access to the inner solar system.

4. Increase the reliability and availability of fusion reactors compared to DT systems because of the greatly reduced radioactivity, the low neutron damage, and the elimination of T breeding; and

5. Greatly reduce the capital costs of fusion power plants (compared to DT systems) by as much as 50% and present the potential for a significant reduction in the COE.

Some key remaining questions are

1. Will the fusion community design future facilities such that they can validate the plasma physics scaling of both DT and D-He^3?

2. Can direct conversion concepts be tested in the near term for tandem mirrors or tokamaks to validate the high conversion efficiencies?

3. Will more detailed tokamak D-He^3 studies be performed to quantify perceived advantages relating to reliability, maintainability, and availability?

4. Will He^3 be extracted from lunar regolith at planned NASA bases in the early twenty-first century?

5. How much will it cost to obtain He^3 from the Moon with or without credit from other volatiles such as H_2, N_2, or C needed by manned lunar bases?

Finally, the concepts presented in this paper tie together two of the most ambitious high-technology endeavors of the twentieth century: the development of controlled thermonuclear fusion for civilian power applications and the utilization of outer space for the benefit of mankind on Earth. Given the talents and resources associated with these programs, it should not be surprising that this coupling has occurred. The main question now is how soon can these programs join forces to prepare for the needs of the twenty-first century?

Acknowledgments. This work was supported in part by the Electric Power Research Institute, the Wisconsin Electric Utilities Research Foundation, NASA, and the Grainger Foundation. The authors also wish to acknowledge the help of scientists in the Fusion Technology Institute, the Wisconsin Center for Space Automation and Robotics at the University of Wisconsin, and the Astronautics Corporation of America. Special thanks are given to H. Attaya, G. A. Emmert, and M. E. Sawan for permission to quote unpublished results.

REFERENCES

Abdou M. A. et al. (1986) Cont. Fusion Reactor Design IV. *Nucl. Fusion, 26,* 1377.

Attaya H., Sawan M. E., and Kulcinski G. L. (1991) Waste disposal of candidate structural materials in fusion reactors utilizing different fuel cycles. *Fusion Technol.*, in press.

Baker C. C. et al. (1980) *STARFIRE—A Commercial Tokamak Fusion Power Plant Study.* ANL/FPP-80-1.

Barr W. L. and Moir R. W. (1983) Test results on plasma direct converters. *Nucl. Technol. Fusion, 3,* 98.

Cameron E. N. (1987) *Titanium in Lunar Regoliths and Its Use in Site Selection.* Wisconsin Report No. WCSAR-TR-AR3-8708.

Emmert G. A., El-Guebaly L. A., Kulcinski G. L., Santarius J. F., Scharer J. E., Sviatoslavsky I. N., Walstrom P. L., Wittenberg L. J., and Klingelhöfer R. (1989) Possibilities for breakeven and ignition of D-He^3 fusion fuel in a near-term tokamak. *Nucl. Fusion, 29,* 1427.

Fermi E. and Szilard L. (1944) Patent No. 2,708,656 applied for December 1944, granted May 18, 1955.

Häfele W. (1981) *Energy in a Finite World.* Ballinger, Cambridge, Massachusetts.

Hawryluk R. J. et al. (1986) TFTR plasma regimes. In *Papers Presented at the 11th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research.* Kyoto, Japan.

Holdren J. P., Chairman (1987) *Summary of the Report of the Senior Committee on Environment, Safety, and Economic Aspects of Magnetic Fusion Energy.* UCRL-53766.

Jacquinot J. et al. (1987) Results of RF heating on JET and future prospects. In *Proc. 7th Int. Conf. on Appl. of Radiofrequency Power to Plasmas,* pp. 220-229.

The JET Team (1986) JET latest results and future prospects. In *Papers Presented at the 11th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research.* Kyoto, Japan.

Kefitz N. (1987) *Population of the World and Its Regions 1975-2050.* Int. Inst. for Appl. Syst. Anal., Laxenburg, Austria.

Kulcinski G. L. (1985) What have fusion reactor studies done for you today? *J. Fusion Energy, 4,* 171.

Kulcinski G. L. et al. (1987) The commercial potential of D-He^3 fusion reactors. *Proc. 12th Symp. Fusion Eng.,* pp. 772-775.

Lawrence Livermore National Laboratory (1984) *MARS-Mirror Advanced Reactor Study.* UCRL-53480.

Lawrence Livermore National Laboratory (1986) *MINIMARS Conceptual Design: Final Report.*

National Commission on Space (1986) *Pioneering the Space Frontier.* Bantam, New York.

Pepin R. O., Nyquist L.E., Phinney D., and Black D. C. (1970) Rare gases in Apollo 11 lunar material. In *Proc. Apollo 11 Lunar Sci. Conf.,* pp. 1435-1454.

Ride S. K. (1987) *Leadership and America's Future in Space: A Report to the Administrator.* U.S. Govt. Printing Office, Washington, DC. 63 pp.

Santarius J. F. et al. (1987) Ra: A high efficiency, D-He^3 tandem mirror fusion reactor. *Proc. 12th Symp. Fusion Eng.,* p. 752.

Santarius J. F. et al. (1988) SOAR: Space orbiting advanced fusion power reactor. In *Space Nuclear Power Systems* (M. S. El-Genk and M. D. Hoover, eds.), pp. 167-176. Orbit, Malabar, Florida.

Schmidt J. et al. (1986) A compact ignition experiment. In *Papers Presented to the 11th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research.*

Schmitt H. H. (1973) Apollo 17 Report on the Valley of Taurus-Littrow. *Science, 182,* 681.

Strachan J. D. et al. (1987) High temperature plasmas in TFTR. *Phys. Rev. Lett., 58,* 1004.

Sviatoslavsky I. N. (1987) *Preliminary He^3 Demand Requirements for Commerical Fusion.* Univ. of Wisconsin Report WCSAR-TR-AR3-8709.

Sviatoslavsky I. N. (1988) *Mobile He^3 Mining System and its Benefits Toward Lunar Base Self-Sufficiency.* Univ. of Wisconsin Report WCSAR-TR-AR3-8808.

University of Wisconsin (1987) *Proposal to NASA for a Space Engineering Research Center on the Space Applications of Fusion Energy.*

U.S. Department of Energy (1987) *Energy Security—A Report to the President of the United States.*

Wilkes W. R. (1978) *He^3 Recovery and Enrichment Technology.* U.S. Dept. of Energy, MLM-2419, p. 102.

Wittenberg L. J., Santarius J. F., and Kulcinki G. L. (1986) Lunar source of He^3 for commercial fusion power. *Fusion Technol., 10,* 167.

N93-13986

SYNERGISM OF ^{3}He ACQUISITION WITH LUNAR BASE EVOLUTION

T. M. Crabb

Orbital Technologies Corporation
402 Gammon Place, Suite 10
Madison WI 53719

M. K. Jacobs

Science Applications International Corporation
1515 Woodfield Road
Shaumbaugh IL 60173

Researchers have discovered that the lunar surface contains a valuable fusion fuel element that is relatively scarce on Earth. This element, ^{3}He, originates from the solar wind that has bombarded the surface of the Moon over geologic time. Mining operations to recover this resource would allow the by-product acquisition of hydrogen, water, carbon dioxide, carbon monoxide, methane, and nitrogen from the lunar surface with relatively minimal additional resource investment when compared to the costs to supply these resources from Earth. Two configurations for the ^{3}He mining system are discussed, and the impacts of these mining operations on a projected lunar base scenario are assessed. We conclude that the acquisition of ^{3}He is feasible with minimal advances in current state-of-the-art technologies and could support a terrestrial nuclear fusion power economy with the lowest hazard risk of any nuclear reaction known. Also, the availability of the by-products of ^{3}He acquisition from the Moon could significantly reduce the operational requirements of a lunar base and increase the commercialization potential of the base through consumable resupply of the lunar base itself, other components of the space infrastructure, and other space missions.

INTRODUCTION

Great advances in the exploration of space will take place in the twenty-first century. Beginning with a space station in low-Earth orbit and moving toward the settlement of the Moon and Mars, the exploration and development of space will broaden mankind's horizons. The establishment of a permanently manned lunar base would create an excellent stepping stone to future space exploration missions. These advanced missions may support development of a large inexpensive power system on Earth through the evolution of a very attractive fusion reaction involving deuterium and an isotope of helium, ^{3}He. The advantages of this reaction vs. fission reactions and conventional D-T fusion include reduced radioactivity due to a reduction of neutrons emitted, improved safety over other fusion reactions and all fission reactions, increased efficiency, and lower electricity costs. Because terrestrial quantities of ^{3}He would not support a fusion energy economy, researchers are looking to the Moon as a source of ^{3}He (*Wittenberg et al.,* 1986). It has been estimated that the Moon contains approximately 1,000,000 metric tons (MT) of ^{3}He from solar wind bombardment over the past 4 b.y.

Here we show how acquisition of ^{3}He affects lunar base development and operation. We summarize a four-phase evolutionary lunar base scenario with initial equipment mass and resupply requirements. Requirements for various ^{3}He mining operations are shown, and available by-products are identified. Impacts of mining ^{3}He on lunar base development include increases in equipment masses to be delivered to the lunar surface and a reduction of lunar base resupply based on availability of by-products. We conclude that the mining of this valuable fusion fuel element greatly enhances the commercial potential of a lunar base.

EVOLUTIONARY LUNAR BASE SCENARIOS

To determine requirements for the establishment of a lunar base, various phases of base development must be identified. Subsystems required for base operation must be defined. Mass, power, and resupply requirements for these operations must be determined to address overall transportation requirements and cost of operations. A four-phase evolutionary lunar base scenario was created from previous work on lunar base concepts and from current technology projections (*Crabb and Jacobs,* 1987a,b). This scenario is used here to assess impacts of integrating ^{3}He mining into lunar base development.

The four phases of the evolutionary lunar base scenario include (1) a man-tended science base; (2) a manned science and technology base; (3) a manned science and manufacturing base; and (4) a manned science, manufacturing, and export base. Each phase builds on an evolutionary operating capability. The base's manned capability grows from 4 to 6 crew members to 15 to 20 crew members over a period of 23 years.

The initial lunar base scenario can support 4 to 6 persons for a 10-day mission. Missions performed at this lunar base would be mainly science oriented. Science missions include geology, life sciences/medicine, astronomy, technology testing, and study of energy systems. No provisions for processing lunar regolith for rocket propellant or other resources are provided in this stage of lunar base development.

The next stage of lunar base development would allow for continuous occupancy of the base by four to six persons. General science operations would be expanded to include specific studies of geology, life sciences/medicine, and technology testing. Oxygen would be produced in this stage via chemical processing lunar regolith by hydrogen reduction of ilmenite using Earth-supplied

hydrogen. A small-scale mining operation would be initiated to supply the base with the needed regolith for oxygen production (6.6 MT lunar regolith per 1 MT oxygen).

In the third stage of lunar base development, continuous support for 10 persons is provided. Carbothermal reduction is added to hydrogen reduction to expand regolith processing capability allowing for production of lunar resources beyond oxygen [29.2 MT lunar regolith per 1 MT oxygen + 1 MT silane (SiH_4) + 0.4 MT silicon for carbothermal reduction]. The additional lunar resources produced can be used for fabrication of structures, solar panels, and various other products useful to the base. Provisions for the manufacture of these types of products must be provided in this stage of base development. Mining operations are expanded to provide the needed additional lunar regolith for manufacturing and production. This expanded mining scenario may include the initial development of a conveyor network to enable acquisition of larger quantities of lunar regolith.

In the fourth stage of the evolutionary lunar base scenario, the base is capable of supporting 15 to 20 persons continuously. To increase the self-sufficiency of the base, a process similar to HF acid leach would be added to the chemical processing facility to obtain aluminum and provide the potential to obtain other elemental resources for structures (8.7 MT lunar regolith per 1.0 MT oxygen + 0.6 MT aluminum). Magma electrolysis is added to obtain iron for structures (132.5 MT lunar regolith per 1.0 MT oxygen + 0.8 MT iron). Shiftable conveyors would be added to the mining scenario to provide the additional regolith needed for manufacturing and production. Shiftable and permanent conveyors could be added as the demand for regolith increases.

Lunar Base Subsystems

The required lunar base subsystems are determined from the three major operations to be performed by a lunar base, which include science, manufacturing and production, and infrastructure/support. These operations expand differently as a lunar base scenario evolves. Table 1 summarizes mass delivery requirements for each subsystem of the evolutionary lunar base scenario.

Science missions are an important part of any lunar base scenario. These missions are needed to provide information on lunar geology, life science/medicine, astronomy, technology testing, and the study of energy systems. The science system for these lunar base scenarios was modeled from the current space station laboratory modules (*JSC*, 1986). In the early stages of lunar base development, one module might support small-scale experiments for many of these science missions. As the base grows, modules dedicated to a specific type of science mission may be added.

The manufacturing and production system is the main contributor to self-sufficiency. While emphasis on this system is low in the early stages of base development, it has the highest priority in an evolved base configuration. Manufacturing and production operations include chemical processing for lunar resources, fabrication of hardware or structures from lunar and terrestrial materials, and mining operations for acquisition of regolith. Chemical processing may only involve extraction of oxygen from lunar regolith in the early stages of base development. As the base grows, processing for additional lunar resources will be required. Fabrication of hardware or structures will only be required in fairly evolved lunar base scenarios, because larger-scale structures and hardware are required before the additional mining and processing operations become cost effective. Mining operations eventually include surface transport vehicles, permanent and shiftable conveyor systems, and beneficiation systems to remove specific grain-size fractions and to remove specific ores from the regolith.

TABLE 1. Subsystem mass requirements for the evolutionary lunar base scenario.

Lunar Base Subsystem	Phase of Evolutionary Lunar Base Scenario Surface payload delivered (MT) 1	2	3	4
Science	25	125	175	200
Manufacturing & Production	—	12	431	1115
Infrastructure	28	58	133	590

The lunar base infrastructure consists of habitats, surface transportation, launch/landing facilities (including a mass driver system), maintenance facilities, and power. The infrastructure can be thought of as a base on which all lunar operations are built. It must provide all resources (mainly life support and regolith processing consumables, electrical and thermal energy, and life support for crew members) to support science and manufacturing operations. The power plant within the infrastructure can be thought of as LP&L (Lunar Power and Light) and must provide sufficient power for all community needs.

The lunar base is capable of utilizing lunar resources after initial operating capability is reached for the second phase of development. Initially, production will be centered on acquisition of lunar oxygen. As the base evolves, structural materials would be needed to ease expansion requirements by using lunar-derived materials. Figure 1 shows the production capability of each phase of base development. The results from science activities may not be quantifiable products, but would contribute to advancing knowledge and technologies for future systems to improve operating efficiencies.

Lunar Base Resupply

Resupply mass requirements include mass for hardware refurbishment, as well as for consumable replenishment. Resupply requirements have been divided into the three major subsystems. Figure 2 summarizes operational resupply requirements for each lunar base subsystem and for each phase of base development.

Resupply for the science system is partly made up of hardware for refurbishment of laboratory modules, but it is mainly made up of science payloads that are delivered from Earth to conduct scientific experiments on the lunar surface.

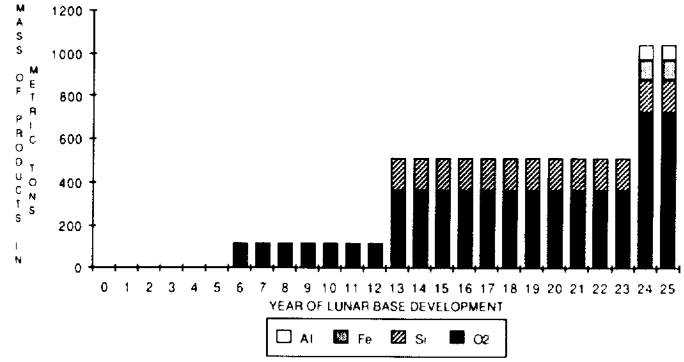


Fig. 1. Annual lunar base production capabilities.

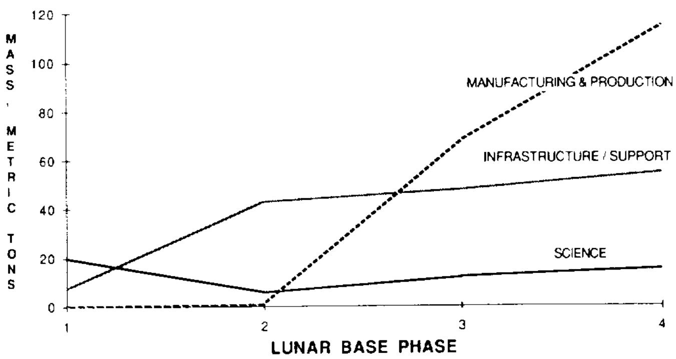


Fig. 2. Lunar base annual resupply masses.

Over 75% of the resupply in the manufacturing and production system is to replenish unrecyled reactants used for processing regolith. Some hardware resupply is required to refurbish failed mining system components. Required resupply for unrecycled reactants/consumables and hardware refurbishment is not assumed to be from a lunar source, although many of the consumables required for regolith processing may be made available from extractions of ^{3}He and other solar wind gases (discussed later). The major contributor to resupply requirements for the infrastructure/support system originates from life-support consumables. Water, the largest consumable in the life-support system, may be available in sufficient quantities as a by-product of a ^{3}He mining operation.

A major advantage of ^{3}He mining at a lunar base is to make quantities of many consumables that would need to be delivered from Earth available from local resources. To identify these benefits, specific quantities of consumable resources required by a lunar base must be identified. Consumable resource requirements can be obtained from analysis of resupply requirements for the manufacturing and production system and the infsrastructure/support system. Resupply breakdowns for these lunar base systems can be found in Table 2. These resupply requirements determine transportation requirements for normal lunar base operation without expansion considerations. Acquisitions of ^{3}He may increase hardware mass supply requirements but can relieve the requirement for consumables to be transported to the lunar surface from Earth.

TABLE 2. Breakdown of consumable resupply.

Lunar Base Subsystem	Phase of Evolutionary Lunar Base Scenario Resupply payload to surface (kg/yr) 1	2	3	4
Process Consumables				
H_2	—	186	372	558
CH_4	—	—	60,000	60,000
HF	—	—	—	33,00
Life-Support Consumables				
H_2O	3,350	1,834	3,668	4,280
O_2	450	247	493	570
N_2	250	137	275	323

LUNAR ^{3}He

Lunar sources of ^{3}He were first discovered in 1970 by R. O. Pepin (*Pepin et al.,* 1970). In 1986, a study conducted by scientists at the University of Wisconsin (*Wittenberg et al.,* 1986) estimated the potential ^{3}He reserves on the Moon to be one million metric tons. Terrestrial sources of this resource are from the decay of tritium and are estimated at a few hundred kilograms per year. Terrestrial quantities of ^{3}He are not sufficient for a large-scale fusion power industry, which would require up to 10 MT of ^{3}He per year (*Kulcinski et al.,* 1988). This section defines requirements of a lunar ^{3}He mining operation and potential by-products that could be acquired with minimal additional resource requirements.

The advantages of fusion energy using ^{3}He are many (*Wittenberg et al.,* 1986; *Kulcinski et al.,* 1988). Approximately 600,000 GJ of energy, or 19 $MW_{th}y$, is released upon burning 1 kg of ^{3}He with deuterium. Thermal-to-electrical conversion efficiency for the D-^{3}He fusion reaction is high, approximately 70%. This would yield an electrical energy content of 11.4 MWy per kg of ^{3}He. Lunar ^{3}He production levels are estimated to start at approximately 10 kg/yr and would increase to several thousand kilograms annually within 30-40 years of the initiator of lunar ^{3}He mining. The impacts on North American energy production are very significant and may prove even more significant on future energy requirements in space.

Lunar ^{3}He sources originate from the solar wind that has bombarded the lunar surface over geologic time (approximately 4 b.y.). Analyses of lunar samples returned from the Apollo missions show helium concentrations in lunar mare regolith of about 30 ppm (*Williams,* 1980). The concentration of ^{3}He in the total helium content has been estimated to be about 300 ppm (*Pepin et al.,* 1970). Although the degree of homogeneity of the mare regolith is yet unkown, 1.11×10^8 kg of unbeneficiated lunar mare regolith would contain about 1 kg of ^{3}He. Because the mare regolith samples collected to date show a high degree of homogeneity, it is assumed that these concentrations are consistent to at least a 3-m depth. Thus, a volume 3 m deep by 25,370 m^2 would contain 1 kg of ^{3}He. Although these estimates are based on lunar sample analyses, further sampling would be required to provide a stronger basis for estimates of ^{3}He concentration in specific sites on the lunar surface and at various depths in the mare regolith.

Because the heat capacity of lunar regolith is so low (0.784 J/g K), regolith should be beneficiated as much as possible to reduce the quantities that must be heated. Because the solar wind is implanted near the surface of each grain in the regolith, smaller grains, which have a higher surface area-to-volume ratio, appear to have higher concentrations of implanted solar wind gases. Thus, beneficiation to remove larger grains can yield reductions of lunar regolith that must be heated by almost 50% while maintaining acquisition of 70-80% of the total ^{3}He available.

Requirements for ^{3}He Acquisition

Helium-3 and other solar wind gas constituents can be removed from lunar regolith through heating. Regolith is collected, beneficiated to a specific grain size fraction, and heated. After heating to approximately 700°C, many of the adsorbed solar wind gases are released. The processing temperature was chosen to optimize the release of helium without release of implanted sulfur, which begins at aproximately 750°C (*Williams,* 1980). Further processing of these gases would remove ^{3}He from the solar wind

gas mixture. Alternative technologies for the various systems required for lunar ^{3}He acquisition are included in Fig. 3.

Two scenarios have been conceptualized for the mining of lunar ^{3}He. The first envisions a mobile miner that would collect the regolith, remove larger grains, and provide thermal energy to release the solar wind gases. The gases would then be collected and stored in storage vesels that would be transported to a central facility for futher processing. The second scenario is a centralized mining concept where sufficient quantities of bulk lunar regolith would be collected and placed on a conveyor system that would transport the regolith to a central facility for processing. A summary of mass and power requirements for each of the ^{3}He mining scenarios is provided in Tables 3 and 4, respectively.

Both ^{3}He mining scenarios are based on an annual ^{3}He production rate of 1 MT. Thermal energy requirements for solar wind gas evolution are based on the heat capacity of lunar regolith and assume 85% heat recovery. The major difference in the solar wind gas extraction subsystem designs among the alternatives is the source of thermal energy. The mobile miner uses a solar collector-concentrator of smaller thermal output, while the centralized system uses the high thermal energy output of a nuclear SP-100 reactor. It should be noted that the requirements for the centralized mining concept depend upon movement of the regolith collection subsystem from a mined area to a different unmined area. Surface preparation requirements for this transportation are not included in either concept. Also, storage requirements for resources obtained following selective condensation are not included in either mining concept.

Mobile vs. Centralized Mining Concepts

To evaluate and compare each mining concept, advantages and disadvantages of each concept must be identified; they can be found in Tables 5 and 6.

When studying the advantages and disadvantages of each concept, many tradeoffs become apparent. Because the solar wind gas extraction system in the centralized concept is in one central location, a nuclear reactor could be used to deliver required thermal power, enabling gas extraction to occur in the lunar day and night. Implementing the use of nuclear reactors on the mobile miner would create many maintenance and safety problems because the systems would be more difficult to closely monitor. An advantage of the mobile miner is that large areas may be easily mined at any distance from the central base. As ^{3}He production requirements increase, and as ^{3}He is removed from regolith near the central base, mining operations must extend to distances far from the central base. Because movement of excavation systems

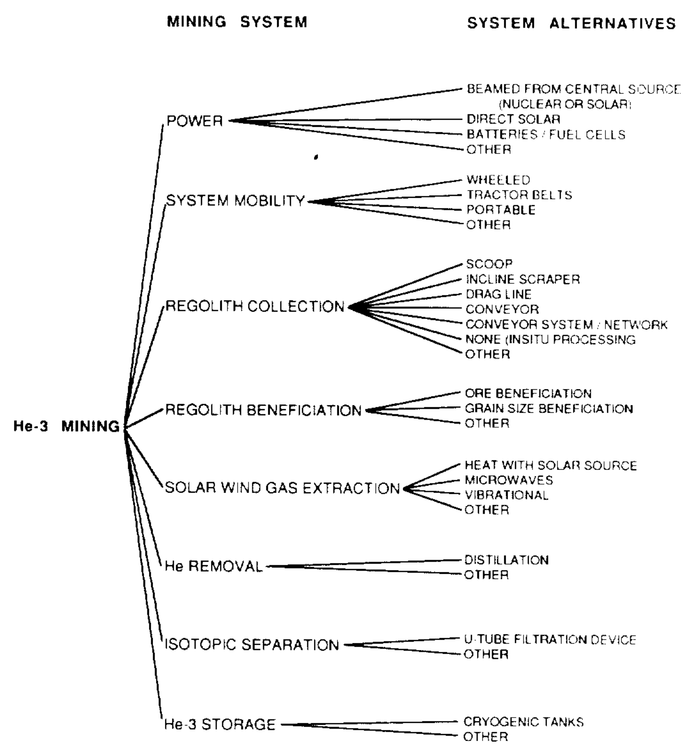


Fig. 3. Helium-3 mining system alternatives.

TABLE 3. Mass summary for ^{3}He mining scenarios.

Lunar ^{3}He Mining Concept	Regolith Collection	Regolith Beneficiation	Solar Wind Gas Extraction	Selective Condensation	Additional
Mobile Miner - 1000 kg ^{3}He/yr					
Bucket Wheel	152				
Internal Regolith Transport	49				
Grain Size Separator		20			
Thermal Power from Direct Solar			242		
Selective Condensation Unit				180	
Gas Storage Vessels					67
Gas Storage Vessel Transport Vehicle					18
Miner Mobility System & Body					83
Totals	201	20	242	180	168
Centralized Concept - 1000 kg ^{3}He/yr					
Bucket Wheel Excavators	200				
Conveyor System	645				
Grain Size Separator		20			
Nuclear Thermal Power			10		
Selective Condensation Unit				180	
Totals	845	20	10	180	

All masses are in metric tons. Total mass for mobile miner = 811 MT. Total mass for centralized concept = 1055 MT.

TABLE 4. Power summary for ^{3}He mining scenarios.

Lunar ^{3}He Mining Concept	Regolith Collection	Regolith Beneficiation	Solar Wind Gas Extraction	Selective Condensation	Additonal
Mobile Miner - 1000 kg ^{3}He/yr					
Bucket Wheel	910				
Internal Regolith Transport	152				
Grain Size Separator		150			
Thermal Power from Direct Solar			4848		
Selective Condensation Unit				5450	
Gas Storage Vessels					—
Gas Storage Vessel Transport Vehicle					242
Miner Mobility System & Body					1110
Totals	1062	150	4848	5450	1352
Centralized Concept - 1000 kg ^{3}He/yr					
Bucket Wheel Excavators	870				
Conveyor System	6105				
Grain Size Separator		150			
Nuclear Thermal Power			5675		
Selective Condensation Unit				5450	
Totals	6975	150	5675	5450	

All power values are in kilowatts. Total power for mobile miner = 12,862 kW. Total power for centralized concept = 18,250 kW.

TABLE 5. Advantages/disadvantages of the mobile miner.

Advantages	Disadvantages
Minimal alteration of lunar surface	Predicted ^{3}He demands would require over 100 mobile miner systems by the year 2050
High degree of automation possible	Operation only during the lunar day reduces potential ^{3}He production rates
No tear-down/set-up requirements for mining different areas far from central base	Because maintenance of several mobile miners, some many kilometers from the central base, is very resource intensive, systems within the miner, must have minimal complexity (or maximum reliability)
Multiple miners can cover a very large surface area	
Operates fairly independently of other lunar base operations	
Has a lower mass per kg ^{3}He obtained than centralized concept	

TABLE 6. Advantages/disadvantages of the centralized mining concept.

Advantages	Disadvantages
Much of the hardware required could be utilized by a lunar base for oxygen production and other mining activities	Has a higher yield than mobile
Operation during the lunar day and night	Moving the mining operation to another location would be very resource intensive
Since many of the gas removal/collection systems are centrally located, servicing/maintenance is less costly than in mobile systems and may be designed with higher levels of complexity using SOA technologies	Because more systems are located in the central facility than with the mobile miner, there will be more significant impacts on the lunar base infrastructure
	Since large quantities of regolith need to be delivered to the central facility for processing, problems of accumulation of processed regolith stockpiles may arise

in the centralized concept would be very costly, the mobile miner has a greater potential to meet long-range ^{3}He production requirements.

A major advantage of the centralized mining concept over the mobile miner is commonality of hardware. The excavation and conveyor systems required by the centralized concept can be used to collect regolith for oxygen and other lunar resource processing schemes. This would reduce the mass delivery requirements for the manufacturing and production lunar base system. The excavation systems of the base and the centralized ^{3}He mining concept are identical. The entire conveyor system mass of the fourth phase of the evolutionary lunar base scenarios could also be provided by the centralized concept. Considerations of shared hardware reduces mass delivery requirements for the manufacturing and production system by 8% for the centralized ^{3}He mining concept.

IMPACTS OF ^{3}He ACQUISITION ON LUNAR BASE DEVELOPMENT

To determine the impacts of mining lunar ^{3}He, we must first identify the advantages and disadvantages of each mining concept. We must then consider how the implentation of each mining concept affects the mass delivery requirements of the lunar base. The delivery of mining hardware generally increases mass delivery requirements, but the use of by-products made available by such mining would reduce the mass delivery requirements and increase the efficiency of the hydrogen/oxygen-based Earth-Moon transportation systems. The value of ^{3}He and the significant quantities of the by-products available enhance the commercialization potential of the lunar base.

Available By-products

Many of the other constituents of the solar wind gas mixture are valuable to lunar base operations and are obtained with minimal additional resource requirements through "synergistic" processing. Table 7 lists these available by-products and the quantities available upon heating lunar regolith to 700°C. The markets for these by-products is discussed later.

Reduction in Lunar Base Logistics

Figure 4 shows the overall mass delivery requirement for the evolutionary lunar base scenarios without ^{3}He mining. The impacts of each ^{3}He mining concept on a lunar base can be determined by comparing the mass delivery requirements of the lunar base without ^{3}He mining to a lunar base implementing a ^{3}He acquisition scenario.

Figure 2 showed resupply requirements for the manufacturing and production system and the infrastructure. Some of the consumables that require resupply may be provided from by-products of ^{3}He acquisition. Table 8 shows the lunar base consumable requirements and the quantities available as by-products of ^{3}He mining scenarios.

It is important to note the quantity of water shown here may be high because of potential water contamination in the Apollo samples (used to derive this data) when returned to and analyzed on Earth. Also, there would be additional requirements to purify the water obtained. Oxygen may be obtained from further processing of CO and CO_2. The effect of supplying lunar base consumables from ^{3}He mining on the overall lunar base scenario development can be seen in Fig. 5. To accurately compare the two ^{3}He mining scenarios, similar criteria must be applied. Both scenarios have similar ^{3}He production rates for each year. Both mining concepts assume mass delivery increases of 25% from one year to the next. Both concepts are capable of obtaining 1000 kg of lunar ^{3}He per year by the initiation of the fourth phase of the lunar base (year 23).

The mass delivery for a lunar base with ^{3}He mining is actually less than the baseline lunar base (without ^{3}He mining) for ^{3}He acquisition rates of 100-300 kg/yr and a lunar base with a permanent crew of 10. This occurs because the ^{3}He mining operation can resupply the lunar base with consumables for life support, atmosphere maintenance, and manufacturing and production processes. In addition to resupplying consumables, the centralized concept delivers all the excavation equipment needed for

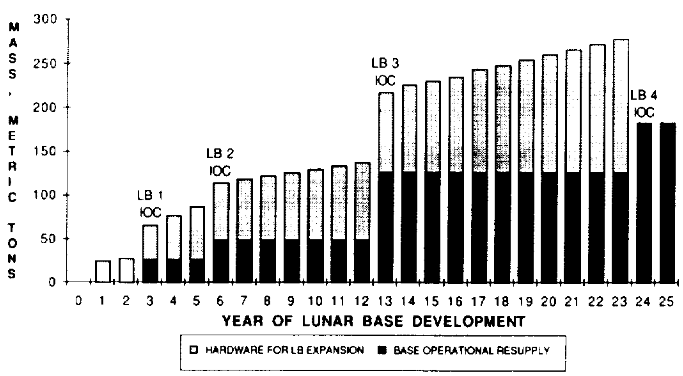


Fig. 4. Overall mass delivery requirements for the evolutionary lunar base scenarios.

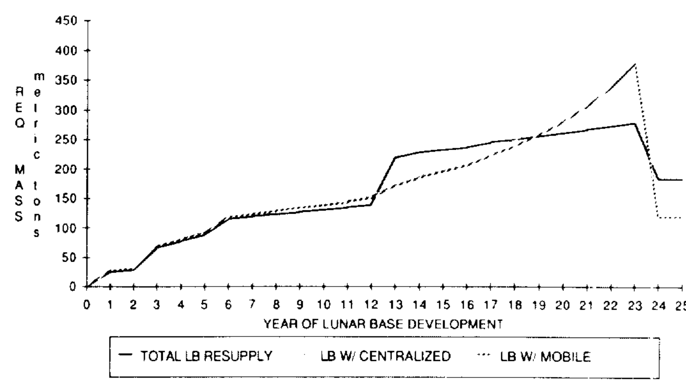


Fig. 5. Base resupply with and without ^{3}He mining.

TABLE 7. Gas release predicted from heating mare regolith to 700°C.

		Concentration, ppm (g/MT)				
Operation	Regolith (MT)	He-3	He-4	H_2	Carbon	Nitrogen
Surface Mining	1	9×10^{-3} 90%	30 90%	50-60 90%	142-226 90%	102-153 90%
Beneficiate <50 μm	0.45	8.1×10^{-3}	27	50	166	115
Heat to 700°C	0.45 (beneficiated)	86% 7×10^{-3}	81% 22	85% 43 (H_2) 23 (H_2O)	3.5% 2% 5% 13.5 (CO) 12 (CO_2 11 (CH_4)	3.2% 4
Per 1 kg He-3	1.37×10^5 (mined)	1 kg	3.1 MT	6.1 MT (H_2) 3.3 MT (H_2O)	1.9 MT (CO) 1.7 MT (CO_2) 1.6 MT (CH_4)	0.5 MT
Minor gases: neon 0.3 MT; argon 0.2 MT						
Per Tonne Regolith into Heater	1 (beneficiated)	0.016 g	49 g	96 g (H_2) 78 g (H_2O)	30 g (CO) 27 g (CO_2) 24 g (CH_4)	9 g
Minor gases: neon 4.8 g; argon 3.2 g						

TABLE 8. Additional resources available from ^{3}He acquisition for lunar base support.

Resource	Application to Lunar Base	Estimated Requirement for 15-20-Person Base* (kg/yr)	kg/kg ^{3}He
H_2O	Life Support Consumable	4,280	3300
O_2	Life Support Consumable	570	2322
N_2	Life Support Consumable	323	500
H_2	Lunar Resource Process Consumable	558	6100
CH_4	Lunar Resource Process Consumable	60,000	1600

* Lunar base includes full-scale mining operations, science facilities, semiclosed life support system, and MMW nuclear power source.

manufacturing and production operations in the fourth phase of the lunar base. The fourth phase is reached by the twenty-third year of base development, but hardware delivery for this phase is begun at year 13. After year 23, no expansion of operations is assumed, and the lunar bases with the ^{3}He mining operations operate with reduced logistic requirements compared to the nonmining option. Also, the effect of ^{3}He mining will be even greater when lunar-derived sources of both hydrogen and oxygen have been realized in the space transportation system design. The total Earth launch mass per pound of payload to the Moon may be reduced by 50% when this source of propellants becomes available (*Crabb et al.,* 1987).

Another measure of the effects of lunar base concepts on the space infrastructure is the amount of mass needed to be launched from Earth to deliver all payloads, transport vehicles, and other support needs to the Moon. To determine Earth launch mass, the lunar mass delivery curves (Fig. 5) are used to generate an annual mission model. The mission model is then manifested on orbital and launch/landing vehicles that are conceptually defined using ASTROSIZE, a computer model used to design conceptual vehicles from propulsion system characteristics, aerobrakes, landing systems, thrust structures, and other factors. Total propellant and vehicle requirements are accounted with various sources of propellants considered. The mission model, with space transportation vehicle descriptions (including OTV and lander design), is entered into ASTROFEST, a computer code that uses the mission model and vehicle descriptions to determine quantities of Earth propellants, lunar propellants, and overall Earth launch mass required. Here the vehicles are sized to account for availability of lunar oxygen and lunar hydrogen if they are available. From these data, the total support of lunar base concepts may be evaluated based on the total Earth launch mass including payloads, propellants, and vehicles. The results are shown in Fig. 6.

The results of the Earth launch mass analysis show that ^{3}He acquisition can reduce the Earth launch burden of establishing a lunar base through the provision of consumable gases and propellants. Without ^{3}He acquisition, O_2 is the most likely propellant candidate from lunar sources. With ^{3}He acquisition, H_2 can also be obtained as a by-product and used for propellant. Using H_2 and O_2 from lunar sources provides enough credits to the lunar base with ^{3}He acquisition to make this scenario less resource intensive than the baseline lunar base without ^{3}He acquisition.

Increase in Lunar Base Commercialization Potential

In addition to reducing resupply requirements, ^{3}He acquisition would enhance the commercialization potential of the lunar base in several ways. The ^{3}He could be used to provide large quantities of power to a lunar base or for the support of other space exploration missions. The by-products could be used by the entire space community. Quantities of ^{3}He could also be shipped to Earth to support the nuclear energy economy of the twenty-first century with the safest form of nuclear power known. These applications of ^{3}He are discussed in the following sections.

Space markets for ^{3}He and its by-products. As fusion technology advances, many new applications of ^{3}He will be determined. Researchers are already investigating fusion-powered space transportation vehicles. In addition to transportation, quantities of ^{3}He could provide sufficient power to conduct tasks that would require large amounts of power. A central power plant on the lunar surface operating on a D-^{3}He fusion cycle could beam sufficient energy via microwaves to run a space station in low lunar orbit. This power plant could also beam energy to other locations on the lunar surface using a network of surface and/or orbital reflectors, thus extending the lunar base's range of operation. This energy could also be used to establish and operate other base camps.

A more immediate market that ^{3}He acquisition opens up is the availability of the by-products of ^{3}He acquisition. By the tenth year of base development, excess quantities of ^{3}He acquisition by-products could be made available for the support of other space activities. These activities include (1) resupplying the space station with life-support and atmosphere-maintenance consumables at a much lower cost than having supplies delivered from Earth, and (2) providing needed resources for a lunar refuel/resupply station for support of other space exploration missions. Figure 7 shows the quantities of by-products that could be made available for uses other than the support of a lunar base. Many other applications of the resources ^{3}He acquisition makes available

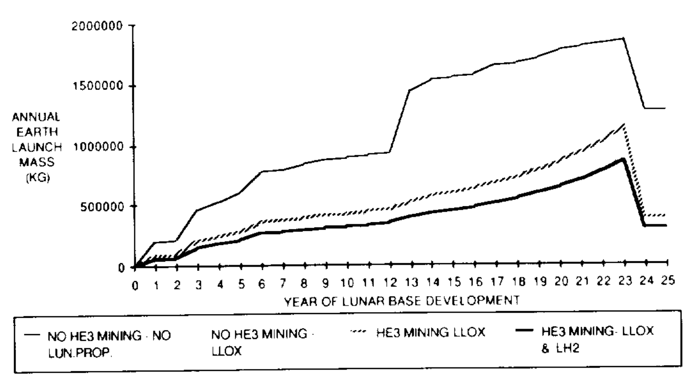


Fig. 6. Total Earth launch mass required for establishment of a lunar base with and without ^{3}He mining.

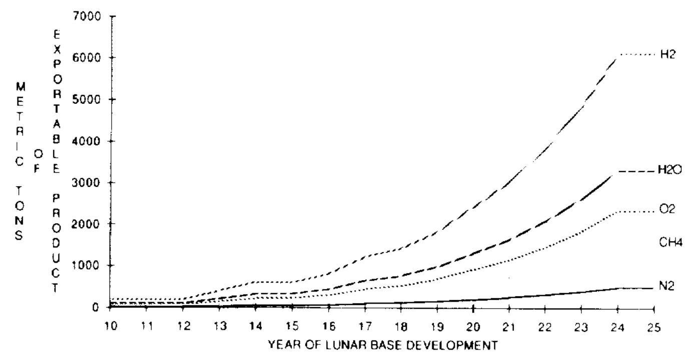


Fig. 7. Annual production of exportable resources from lunar ^{3}He acquisition by-products.

may be discovered as human presence in space grows. The availability of these resources significantly enhances the feasibility of many space exploration missions.

Terrestrial market for ^{3}He as a fusion fuel. As the twenty-first century approaches and fossil fuel supplies diminish, Earth's economy will require much greater amounts of power and energy. Nuclear power seems to be an answer to the problem, but the safety hazards associated with fission reactors has sparked sufficient public concern to hold up development of more nuclear power plants. Nuclear fusion has significantly lower safety risks, and the D-^{3}He cycle has the lowest safety risk factor of any of the known fusion cycles. Although terrestrial quantities of ^{3}He are not sufficient to support large-scale D-^{3}He fusion power development, lunar ^{3}He is abundant enough to support large-scale fusion power on Earth and may provide a strong impetus to return to the Moon on a commercial and cost-effective basis.

SUMMARY AND CONCLUSION

We have shown the value of ^{3}He, a resource scarce on Earth but relatively abundant on the Moon. An evolutionary lunar base scenario was presented, and impacts of two ^{3}He acquisition concepts on this base were determined. A centralized ^{3}He mining concept, in which regolith is excavated and returned to a central facility where the ^{3}He is removed, has a more significant impact on the lunar base than the mobile miner concept, in which solar wind gases are extracted from lunar regolith, and the gas storage vessels are returned to the central facility for further processing. The availability of ^{3}He acquisition by-products reduces the operating requirements of a lunar base and provides the base with greater potential for commercialization by making these by-products available for the support of other space missions. Finally, lunar ^{3}He could support a terrestrial nuclear power economy with the lowest safety risk of any nuclear reaction known. We conclude that ^{3}He acquisition enhances the feasibility of establishing a permanently inhabited lunar base in the early part of the twenty-first century.

REFERENCES

Cameron E. N. (1987) *Geological Aspects of He-3 from the Moon.* Arizona Geological Society, Tucson.

Cameron E. N. (1988) Mining for helium—Site selection and evaluation (abstract). In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century,* p. 47. Lunar and Planetary Institute, Houston.

Crabb T. M. and Jacobs M. K. (1987a) *He-3 Mining Techniques.* Internal Report for the Wisconsin Center for Space Automation and Robotics (WCSAR), Madison.

Crabb T. M. and Jacobs M. K. (1987b) *Preliminary Lunar Base Scenario Design.* Internal Report for the Wisconsin Center for Space Automation and Robotics (WCSAR), Madison.

Crabb T. M. and Jacobs M. K. (1988) *He-3 Acquisition.* Internal Report for the Wisconsin Center for Space Automation and Robotics (WCSAR), Madison.

Crabb T. M., Teeter R. R., and Jacobs M. K. (1987) *Lunar Surface Base Propulsion System Study.* NASA Contract NAS9-17468. Astronautics Technology Center, Madison.

JSC (1986) *Space Sation Reference Configuration.* JSC-30255, NASA Johnson Space Center, Houston.

Kulcinski G. L., Sviatoslavsky I. N., Santarius J. F., and Wittenberg L. J. (1988) Fusion energy from the Moon for the 21st century (abstract). In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century,* p. 147. Lunar and Planetary Institute, Houston.

Pepin R. O., Nyquist L. E., Phinney D., and Black D. C. (1970) Rare gases in Apollo 11 lunar material. *Proc. Apollo 11 Lunar Sci. Conf.,* pp. 1435-1454.

Williams R. J. (1980) *Handbook of Lunar Materials.* NASA RP-1057.

Williams R. J., McKay D. S., and Giles D. (1979) Mining and beneficiation of lunar ores. In *Space Resources and Space Settlements.* NASA-SP-428.

Wittenberg L. J., Santarius J. F., and Kulcinski G. L. (1986) Lunar source of ^{3}He for commercial fusion power. *Fusion Technol., 10,* 167.

PHYSICAL PROPERTIES OF CONCRETE MADE WITH APOLLO 16 LUNAR SOIL SAMPLE

N93-13987

T. D. Lin, H. Love, and D. Stark

Construction Technology Laboratories
5420 Old Orchard Road
Skokie IL 60077

SUMMARY

On March 6, 1986, the National Aeronautics and Space Administration (NASA) awarded Construction Technology Laboratories (CTL) 40 g of lunar soil. The award was made based on a CTL proposal to NASA that lunar soils and rocks could be used as concrete aggregates and as raw materials for manufacturing cement and water. These ingredients could then be used to produce concrete for the construction of lunar bases.

This paper describes the first phase of the long-term investigation for the construction of concrete lunar bases. In this phase, petrographic and scanning electron microscope examinations showed that the morphology and elemental composition of the lunar soil made it suitable for use as a fine aggregate for concrete.

Based on this finding, calcium aluminate cement and distilled water were mixed with the lunar soil to fabricate test specimens. The test specimens consisted of a 1-in cube, a ½-in cube, and three $0.12 \times 0.58 \times 3.15$-in beam specimens. Tests were performed on these specimens to determine compressive strength, modulus of rupture, modulus of elasticity, and thermal coefficient of expansion.

Based on examination of the material and test results, it is concluded that lunar soil can be used as a fine aggregate for concrete.

MATERIALS

Materials used in the fabrication of the test specimens are described below.

Fine Aggregate

The lunar soil sample as shown in Fig. 1 and a lunar soil simulant consisting of a glassy rhyolite sand were used as fine aggregates for fabricating test specimens.

Microscopic Analysis of Lunar Sample

Particles of lunar soil were subangular to subrounded in shape and were somewhat friable. They appeared to have a relatively high porosity. It was estimated that 40-50% of the sample consisted of white grains, while 50-60% consisted of grayish black, glassy-appearing grains. The white particles were more friable than the grayish black particles.

In polarized light, the white particles were determined to be wholly crystalline, and consisted of 99% plagioclase feldspar in the compositional range of bytownite bordering on anorthite. About 80-90% of this feldspar showed a high degree of undulatory extinction, and about 10-20% of the feldspar was twinned. Less than 5% of the plagioclase showed uniform extinction. Traces of glass material, pyroxene, and opaque minerals were also present.

The dark gray to black particles were crystalline, somewhat friable, relatively fine-grained, and subrounded in shape. In polarized light, they were found to consist of about 60-75% plagioclase feldspar in the compositional range of bytownite bordering on anorthite, and 25-40% of the particles consisted of minerals in the pyroxene family. Traces of opaque minerals, possibly iron-rich, were also present. Optical characteristics of the feldspar were similar to those of the white particles except that individual crystals were of much smaller size.

Glassy clear particles were present in trace amounts. These particles consisted of individual crystals of plagioclase feldspar in the compositional range of bytownite to anorthite.

Electron Microscopic Analysis of Lunar Sample

A portion of the lunar sample was analyzed under an ISI-SX40 scanning electron microscope (SEM) equipped with a Tracer Northern Energy Dispersive X-Ray (EDX) spectrometer system to determine the morphology and elemental composition.

Electron microprobe analysis (EMPA) spectra indicated that the major elements in the sample were Ca, Al, and Si. Minor elements,

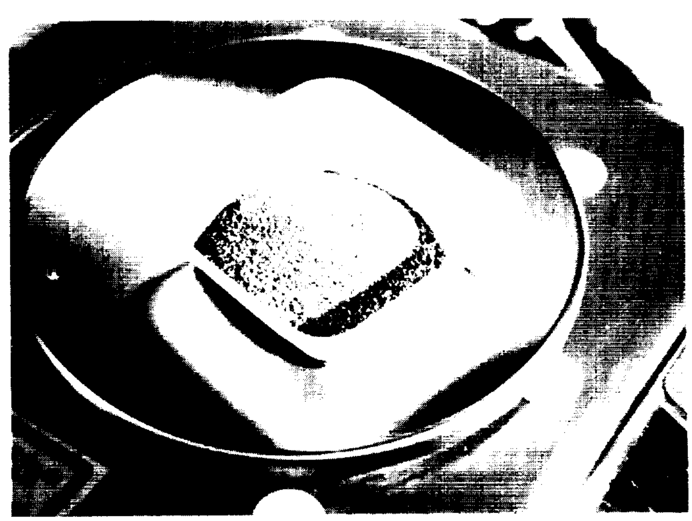


Fig. 1. 40-g graded lunar soil.

listed in the order of abundance, were Mg, Fe, (Ka-K_β), Ti, Na, and K. Many of the particles examined had two good cleavage directions oriented at approximately 90° to one another. This indicated a crystalline structure.

The 40-g graded lunar soil sample had a similar particle size distribution as the graded Ottawa sand used in the preliminary test program (*Lin,* 1985a). Table 1 shows the particle size distribution of the lunar soil sample.

In summary, the lunar material analyzed consists primarily of particles of anorthite, a triclinic mineral ($CaAl_2Si_2O_8$) with two directions of cleavage 86° to one another. The measured volume of the 40 g of lunar soil was 29.2 cm^3, the bulk unit weight was 1.37 g/cm^3, the void percentage was 45%, and the specific gravity was 2.5 g/cm^3.

TABLE 1. Particle size distribution of the 40-g lunar soil sample.

Seive	Retained Weight (g)
No. 16 (1.18 mm)	0.0
No. 30 (600 μm)*	1.6
No. 40 (425 μm)	12.4
No. 50 (300 μm)	18.0
No. 100 (150 μm)	8.0
TOTAL	40.0

*1 $\mu m = 10^{-6}$m.

Lunar Soil Simulant

Following procedures cited in *ASTM* (1985, Designation C 136-84a), natural Ottawa sand and crushed glassy rhyolite were sieved to produce fine aggregate with the same particle size distributions as the lunar soil shown in Table 1. The glassy rhyolite is of acid volcanic material that consists of low calcium, high sodium, and high potassium. The material is a highly absorptive, good quality aggregate.

Bulk unit weight of the rhyolite sand was 1.2 g/cm^3, while its specific gravity was 2.34 g/cm^3.

Cement

Because calcium aluminate cement could be made from lunar materials (*Lin,* 1985b), the commercial calcium aluminate cement was used for the mortar mixes. The specific gravity was 3.08 g/cm^3.

Water

Distilled water was used for all mixes.

FABRICATION AND CURING OF SPECIMENS

The following describes the fabrication and curing of the specimens.

Molds

Three cube molds with ½-, 1-, and 2-in sides were used for casting cube specimens, while a plastic rectangular mold was used to cast the beam specimens.

Mix Proportions

ASTM Designation C 109-84 (*ASTM,* 1985) recommends a water-cement ratio of 0.485:1 and a sand-cement ratio of 2.75:1 for portland cement used in mortar mixes. No ratios are specified for calcium-aluminate cement. However, to maintain the recommended 0.485:1 water-cement ratio for calcium-aluminate cement and to achieve a suitable workability for the cement, the recommended 2.75:1 sand-cement proportion was altered.

The procedure used to select a suitable sand-cement ratio was selected to produce a flow of 110 ± 5% as described in section 8.3 of ASTM Designation C 109-84 (*ASTM,* 1985). Six trial mixes were prepared using highly absorptive glassy rhyolite of the same particle size distribution as that of the lunar soil sample. From these tests proportions of 1.75:1.00:0.485 (sand:cement:water) were selected for the test program.

Fabrication

The mixing, casting, and curing procedures are presented in *Lin et al.* (1986).

Determination of Specimen Age for Tests

During the hydration process, calcium aluminate cement behaves in a substantially different manner than portland cement. The process of hydration is described in *Neville* (1975). In general, the strength decreases as the duration of water exposure increases. For this reason, 24 1-in cubes made with graded Ottawa sand were tested to determine their compressive strengths in relation to specimen ages. The test results show that cubes between three and four days old would give the optimum strength. The 3½-day age was thus selected for testing the cube specimens.

TEST SPECIMENS

A 1-in cube, a ½-in cube, and three 0.12 × 0.59 × 3.15-in beam specimens were fabricated from the lunar soil and calcium aluminate cement mortar. In addition to these specimens, 18 companion specimens (6 of each kind) were fabricated using the simulated lunar material made with glassy rhyolite and calcium aluminate cement.

COMPRESSION TESTS

Cube specimens were tested in a compression testing machine. Figure 2 shows a diagrammatic view of the loading portion of the compression machine with a 1-in-cube specimen positioned

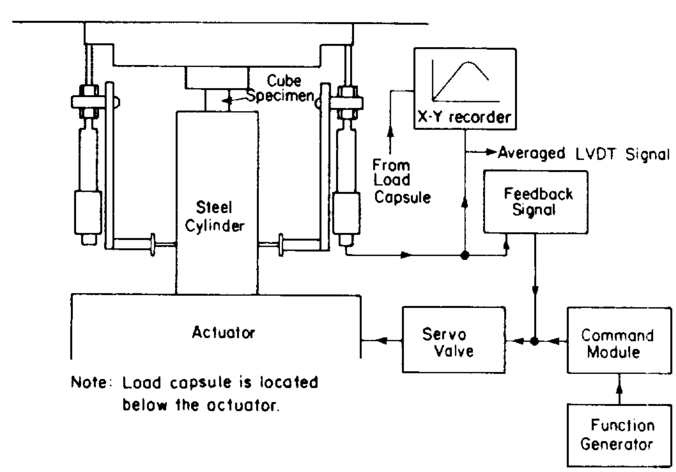


Fig. 2. Closed-loop system of compression test.

below a $3 \times 3 \times 1.5$-in steel plate. The steel plate is secured to the center of the upper bearing block of the closed-loop system.

During the compression test, an input signal is fed into the function generator. The feedback signal is compared with this input signal (in the function generator) by the command module. The difference between the two signals generates a variational signal and the servovalve controls the movement of the platen such that this variational signal is minimized.

Prior to load application, the spherically seated upper bearing block was checked for freedom to tilt. A slight load was applied to ensure full contact between the steel plate bearing block and the test cube. Subsequently the bearing block was fixed and the load was applied slowly to follow the programmed deflection control curve. The rate of loading was controlled to produce a cube contraction of approximately 10 μin/sec. In general, the test load reached a maximum in 20 min and then slowly decreased. Each compression test was completed in about 45 min.

Figure 3 shows the stress-strain curve for a cube made with the lunar soil sample and for a representative companion cube made with the highly absorptive rhyolite simulant obtained during the compression tests. Compressive strength for the lunar cube was 10,970 psi. The average compressive strength of the companion cubes was 7960 psi.

Static moduli of elasticity were estimated to be 1.8 million psi for the lunar cube and 1.1 million psi for the cubes made with the rhyolite. These values were calculated by taking the steepest slope of the rising portion of the stress-strain curve shown in Fig. 3.

The longitudinal and lateral deformations of test cubes under the compressive load were recorded manually. From these data, Poisson's ratios were calculated. Calculations were made up to the peak load of each test. No lateral deformations were observed in the cube made with the lunar soil for stresses below 6600 psi. The cube made with rhyolite did not show any appreciable lateral deformation until a stress of 4800 psi was reached. Figure 4 shows calculated Poisson's ratios of both types of cubes in graphical form. At peak load, Poisson's ratio was 0.39 for the lunar soil mix and 0.27 for the rhyolite mix.

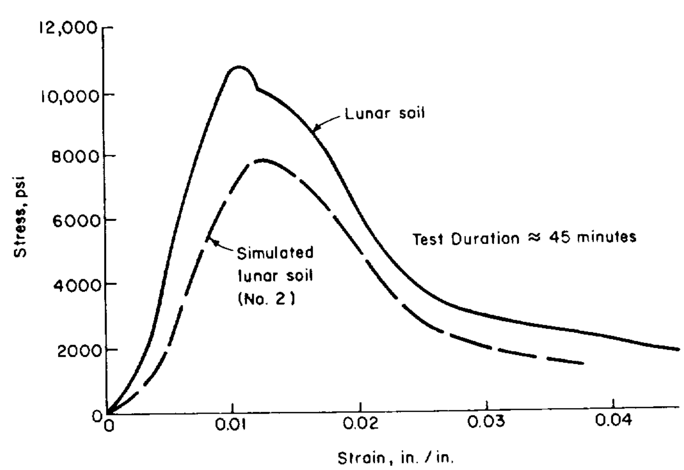


Fig. 3. Measure stress-strain curves.

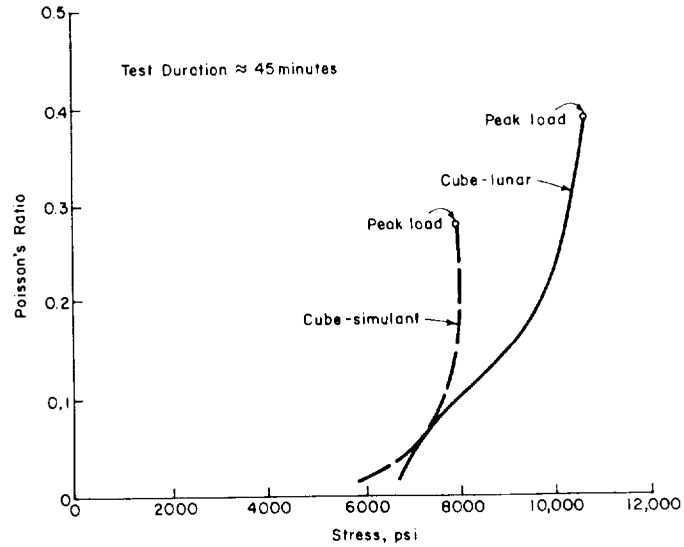


Fig. 4. Poisson's ratio of cubes made with lunar soil and simulated lunar soil.

MODULUS OF RUPTURE

One beam made with the lunar soil mix and three beams made with the rhyolite mix were tested using an Instron testing machine to determine flexural strength. Figure 5 shows a diagrammatic view of the flexural test set-up. Each beam specimen was subjected to two concentric loads at the third points of the span.

The section modulus, Z, of each beam was calculated from its geometric properties. Maximum bending moment was calculated using the equation

$$M = \frac{PL}{6}$$

where P is the maximum load at rupture and L is the span length between supports. In this case, L was 3.06 in (78 mm). The modulus of rupture was obtained by dividing M by Z. The average moduli of rupture for beams made with simulated lunar material was 1244 psi, while that of the beam made with the lunar material was 1206 psi.

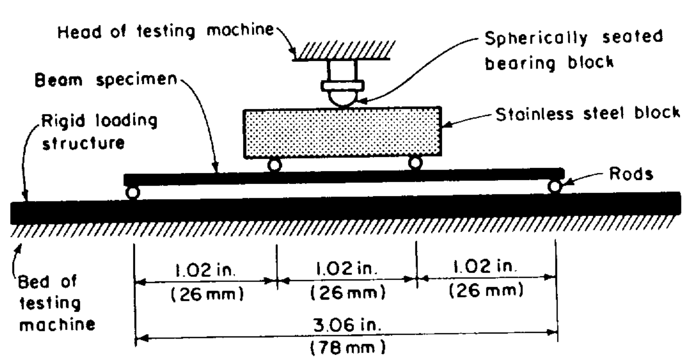


Fig. 5. Diagrammatic view of flexural test set-up.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

DYNAMIC MODULUS OF ELASTICITY

The dynamic modulus of elasticity of the hardened mortar was determined with a sonometer. Measurements of the fundamental flexural resonance frequencies of beam specimens were made in a glove box to ensure a CO_2-free atmosphere, a controlled relative humidity, and a temperature of 75°F.

The beam was supported near a node and vibrated by a wire clip driven by a crystal phonograph cartridge. The other end of the specimen was supported at a node by a soft foam plastic pad. Vibration was detected by a wire probe cemented to a Sonotone 3P-1S ceramic cartridge. The cartridge was mounted in a modified Rek-o-Cut S-320 tone arm. Stylus pressure was adjusted to the minimum required to maintain contact between the specimen and probe. The arrangement is shown in Fig. 6. Dynamic modulus of elasticity for the beam made with lunar soil mix was 3.12 million psi, while the average modulus of elasticity for the beams made with the rhyolite mix was 2.81 million psi.

It is not uncommon that the modulus of elasticity obtained by the resonant method is higher than that obtained by the static method. This is due to the fact that in the static procedure, the cube under sustained load experiences creep. The creep strains add to the total elastic-plastic deformation resulting in a lower modulus of elasticity.

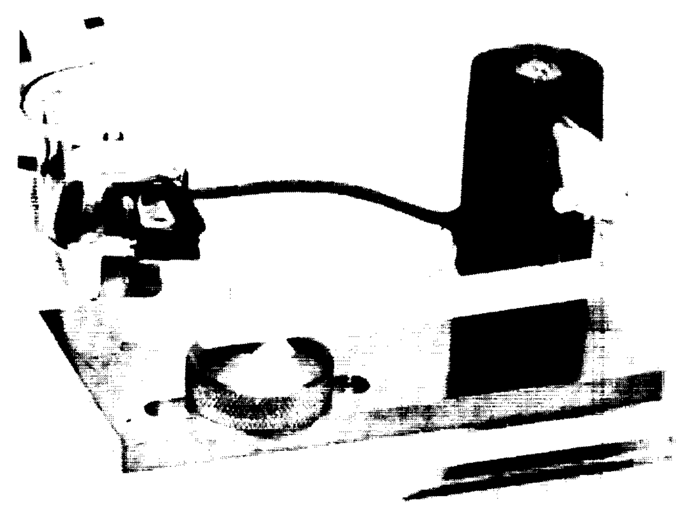


Fig. 6. Measurement of fundamental flexural resonance frequencies.

THERMAL EXPANSION COEFFICIENTS

Figure 7 shows the test set-up of a commercially manufactured dilatometer and a heating/cooling unit for measuring thermal expansion of beam specimens.

Thermally induced deformations of the specimens were transferred through a fused silica rod attached to an Invar bar that rode on ball-bearing pulleys. The end of the Invar bar rested against the plunger of a dial gauge with a calibrated sensitivity of 0.002 mm. Pressure from the light spring of the dial gauge kept the specimen in contact with the closed end of the fused silica tube.

The core of a linear variable differential transformer (LVDT) was mounted axially on the outer end of the dial gauge plunger. Housings for the dial gauge and LVDT were mounted on an adjustable assembly fixed to the slate base. In addition to lightly loading the specimen, the dial gauge was also used to calibrate the response of the LVDT.

Length changes measured by the LVDT included a component caused by thermal expansion of the fused silica tube and rod used to contain the specimen. Expansion of the fused silica components was approximately 2-7% of the length changes of the specimen. Data were corrected for this effect using results of calibration tests on fused silica specimens (*Cruz and Gillen*, 1980).

Thermal expansion of the specimen measured by the LVDT and specimen temperature measured by thermocouples were continuously recorded on an X-Y plotter. Each specimen was subjected to heating and cooling for 2 complete cycles to determine its response to temperature changes that varied from -100° to 350°F.

Measured data were used in calculating coefficients of thermal expansion at elevated temperatures as well as low temperatures. A 5% correction was made for each computed value to compensate for the thermal expansion of the fused silica rod. The average thermal expansion coefficient for beams made with lunar sample was 2.9 millionth in/in/F, while the average thermal expansion coefficient for beams made with rhyolite mix was 3.5 millionth in/in/F.

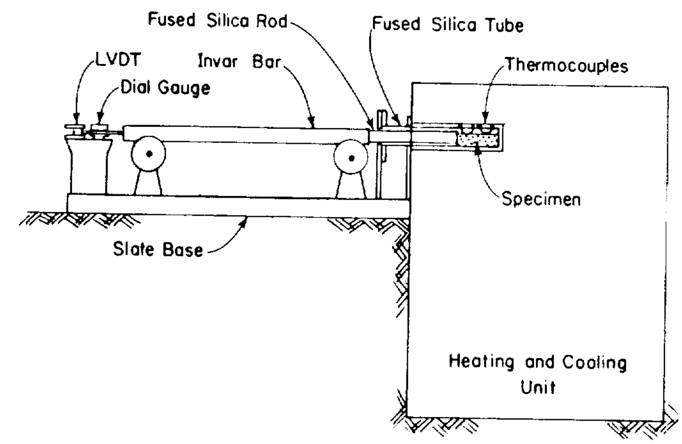


Fig. 7. Commercially manufactured dilatometer.

EXAMINATION OF LUNAR CUBE AFTER TEST

Following the determination of compressive strength, the tested 1-in cube was examined microscopically to characterize the microstructure of the mortar. A stereomicroscope with a magnification range from 7 to 35 was used for this work.

Microscopic examination revealed that the calcium aluminate cement paste matrix was light brown in color and contained a uniform distribution of entrapped air voids. The estimated amount of air voids was 8% by volume of mortar. The paste matrix displayed a uniform intimate bond with the aggregate particle. Esentially, there were no entrapped air voids in direct contact with the particles.

The examination also revealed that fractures that developed during compression testing almost invariably passed through aggregate particles. Only in a few cases did cracks pass around the particles at the paste-aggregate interfaces. In addition, virtually

no aggregate sockets were visible on fractured surfaces. This further attests to the tendency of cracks formed during the compression test to pass through the aggregate particles.

ANALYSIS OF RESULTS

Mechanical properties of the lunar soil are governed by the distribution of grain sizes, the angularity of the grains and its porosity. The lunar soil sample had particle sizes ranging from about 0.1 to 0.8 mm. Particles were either subangular or subrounded in shape. It should be noted that particle shape and surface texture have a greater influence on properties of fresh concrete than on properties of hardened concrete. Rough-textured, angular, elongated particles require more water to produce a workable mix than do smooth, rounded, compacted aggregates. This means that the use of lunar soil as aggregate for a concrete mix will require more water than terrestrial sand does.

The bond between cement paste and a given aggregate generally increases as particles change from smooth and rounded to rough and angular. This increase in bond is a consideration in selecting aggregates for concrete where either high flexural strength or high compressive strength is needed. Test data revealed that the lunar soil has suitable physical properties for use as a fine aggregate.

For aggregate of the same grading, the water requirement for mixing tends to increase as aggregate void content increases. The lunar soil is dry and has 45% void content, 5% higher than that of graded Ottawa silica sand. Again, the lunar soil tends to require more water to produce workable concrete than the smooth, rounded Ottawa sand.

An examination of the lunar soil sample using the SEM revealed that lunar soil includes breccia, lithic grains, mineral grains, glass fragments, and lunar agglutinates. Some grains developed microfractures due to impact of micrometeorites. The immediate concern for use of lunar soil in making concrete was the effect of agglutination and microfractures on concrete strength.

Careful examination of expanded shale lightweight aggregates commonly used in construction today shows that a greater percentage of the material is composed of agglutinates formed during the sintering process at temperatures ranging from 1800 to 2220°F. It appears that the agglutinated joints often develop strength higher than the strength of the expanded shale itself.

Test results of the cube specimen made with the lunar soil sample and examination of the tested cube provide convincing evidence that the agglutination and microfractures caused no negative effect on the cube strength.

Mature lunar soil consists of about 110 ppm solar-wind H and noble gases such as Ar and He (*Morris,* 1983). It is believed that the gas-rich surface of soil particles has no drawback on the cube strength; on the contrary, it may improve the quality of concrete.

For example, the use of admixtures will help explain this phenomenon. In the process of making concrete, air-entraining agents are often used to create air bubbles and thus to increase the durability of the concrete. This demonstrates that N, about 78% in air, has no negative effect on the strength of concrete. Argon and He, like N, are inert gases and are believed to have no effect on cement hydration.

CONCLUSION

Forty grams of lunar soil were evaluated to determine if the material was suitable as fine aggregate for making mortar specimens. Examination by optical microscope showed that angularity of the particles would be likely to cause lunar concrete mixes to require more mixing water than well-rounded terrestrial sands. However, the observed angularity of lunar soil particles would tend to increase the bond between cement paste and aggregate, thereby providing increased strength when compared with well-rounded sands. Slightly higher water requirements would also result from the higher void content and dry conditions observed for lunar soil.

Scanning electron microscope examination showed agglutination and microfractures similar to those found in manufactured lightweight aggregates, and the results of cube tests provide convincing evidence that no negative effects are caused by the agglutination and microfractures. Similarly, the gas-rich surface of lunar soil particles should improve the quality of concrete or have no effect. Finally, the data obtained provide scientific evidence that lunar soil can be used to produce quality concrete for construction on the Moon or in space.

Acknowledgments. The authors would like to express their gratitude to NASA for awarding the 40 g of graded lunar soil collected during the Apollo 16 mission.

REFERENCES

ASTM (1985) *Annual Book of ASTM Standards.* American Society for Testing and Materials, Philadelphia.

Cruz C. R. and Gillen M. (1980) *Thermal Expansion of Portland Cement Paste, Mortar, and Concrete at High Temperatures.* PCA Publication RD074.01T.

Lin T. D. (1985a) *Testing Concrete Specimens Made with Lunar Soil.* Report to NASA.

Lin T. D. (1985b) Concrete for lunar base construction. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 381-390. Lunar and Planetary Institute, Houston.

Lin T. D., Love H., and Stark D. (1986) *Testing Concrete Specimens Made with Lunar Soil.* Report to NASA.

Morris R. V. (1983) *Handbook of Lunar Soils. Parts I and II.* NASA Planetary Materials Branch, Publication 67.

Neville A. (1975) *High Alumina Cement Concrete.* Wiley, New York.

THE POSSIBILITY OF CONCRETE PRODUCTION ON THE MOON

N93-18983

Noboru Ishikawa, Hiroshi Kanamori, and Takeji Okada

Institute of Technology
Shimizu Corporation
No. 4-17
Etchujima 3-chome
Koto-ku
Tokyo 135
Japan

When a lunar base that stands on the Moon for a considerable period is constructed, most of the materials for the construction would be natural resources on the Moon, mainly for economical reasons. In terms of economy and exploiting natural resources, concrete would be the most suitable material for construction. This paper describes the possibility of concrete production on the Moon. The possible production methods are derived from the results of a series of experiments that were carried out taking two main environmental features, low gravity acceleration and vacuum, into consideration.

INTRODUCTION

When the base that permanently stands on the Moon is built, most of the materials required for construction should be produced from natural resources on the Moon.

The ingredients of lunar soil and rocks have been investigated in detail in the Apollo program. It is proposed that, as the construction material of the lunar base, concrete can be manufactured from cement that is produced with soil and rocks on the Moon. Concrete has the following advantages for use as the construction material: (1) Raw materials for concrete exist abundantly on the Moon; (2) It has a simple production process compared with other structural material; (3) The production process requires less energy; and (4) Other technologies are not required to form structures.

On the assumption that materials required for concrete production are easily obtained on the Moon, this study examines the influence of low gravity and high vacuum, and evaluates the possibility of concrete production under the natural environment of the Moon.

INFLUENCE OF LOW GRAVITY

The segregation that originates in the difference in specific gravity of materials constituting concrete rarely happens under low gravity. Such a distinctive peculiarity can be disadvantageous to the acquisition of dense concrete. A fundamental test was performed to examine how low gravity affects the quality of concrete.

The influence of low gravity is extrapolated from the results of the influence of high gravity. This is because very few hours of a state of low gravity can generally be gained on Earth, and an experiment of a time-consuming reaction, such as hydration of cement, is extremely difficult to perform.

As a specimen, mortar that has s/c = 2 and w/c = 65% (where c is high-early-strength portland cement) was used. First of all, a fixed amount of well-mixed mortar was placed into a centrifugal separation machine. Second, five hours of a particular degree of acceleration was given to the specimen [five different degrees of acceleration (1 *g*, 40 *g*, 112 *g*, 300 *g*, and 1062 *g*) were set] and the amount of bleeding water was measured. Finally, the mortar was allowed to cure for seven days and the density and compressive strength of the mortar were measured.

The results of the experiment are shown on Table 1. As the acceleration of gravity increases, the amount of bleeding water, density, and compressive strength increase. Moreover, these values and the logarithm of gravity (log *g*) have near-linear relationships. Figure 1 shows the changes in compressive strength and an equation representing their relation.

Based on this result, the compressive strength of mortar under low gravity on the Moon (1/6 *g*) is assumed to be 10% lower than that under Earth's gravity. If concrete is used for this experiment, the reduction in compressive strength would be around 10%. Consequently, low gravity would not seriously affect the quality of concrete.

TABLE 1. The properties of mortar influenced by high acceleration.

Acceleration of Gravity (*g*)	Amount of Bleeding Water (ml)	Density (g/cm)	Compressive Strength (MPa)
1	1.1	2.15	28.2
40	2.6	2.18	33.0
112	2.8	2.20	29.0
300	3.6	2.24	38.1
1062	3.9	2.24	42.2

INFLUENCE OF VACUUM

When a concrete structure is built on the Moon, concrete is exposed to a vacuum environment at the stage of execution somewhere between the production of concrete and the construction of the structure. If fresh or hardening concrete is exposed to vacuum, the quality of the concrete would be somewhat influenced. Experiments were performed to see how vacuum influences concrete.

A specimen was tempered under normal temperature and 1 atm and cured under a normal state (20.1°C) for a fixed period (precuring period). Then, concrete had w/c = 54.9%, s/a = 40%,

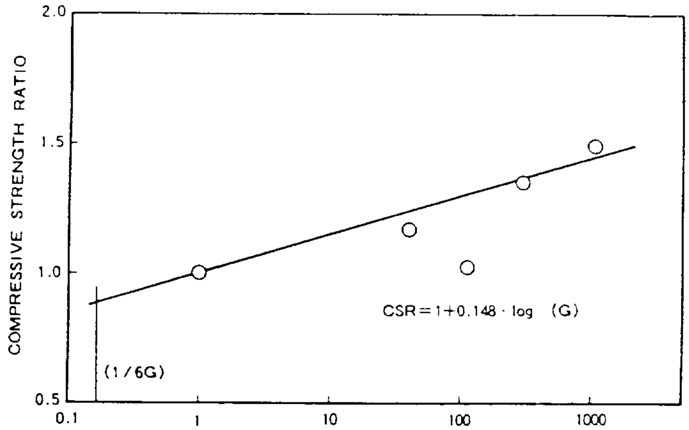


Fig. 1. Influence of acceleration of gravity on CSR, which is the ratio of compressive strength of mortar under high gravity vs. that under 1 *g*.

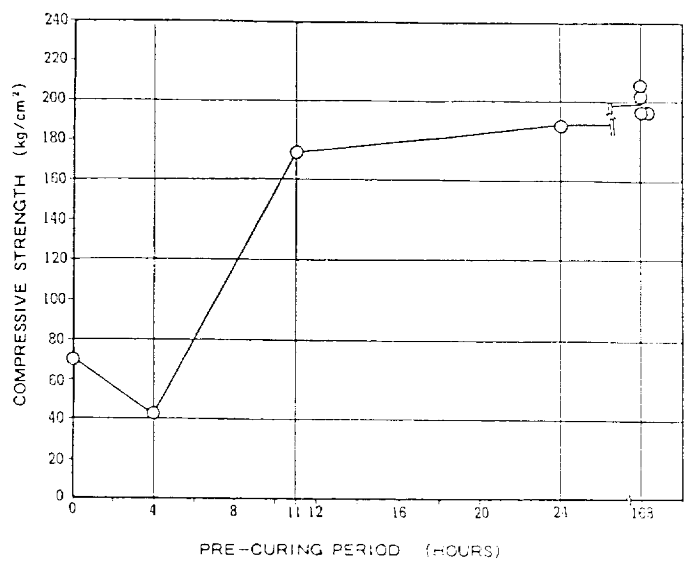


Fig. 2. Influence of precuring period on compressive strength of concrete.

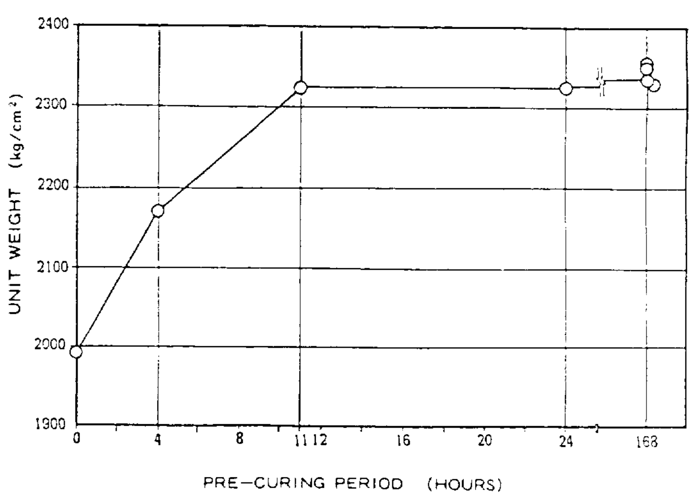


Fig. 3. Influence of precuring period on unit weight of concrete.

and 10 cm of slump. Normal portland cement was used for this experiment.

Changes in compressive strength and unit weight of concrete in various precuring periods are shown in Figs. 2 and 3. When the precuring period was less than four hours, compressive strength and unit weight of hardened concrete were far less than those of the specimen with standard curing; nevertheless, it would hold the moisture required by hydration, even if it is exposed to vacuum. Therefore, a porous structure created inside the concrete by expansion and departure of air bubbles in the concrete and evaporation and diffusion of moisture, causes reduction of those properties. This porosity inside concrete was confirmed with the use of a scanning electron microscope.

Based on this result, concrete should not be exposed to vacuum until a certain setting point is reached because vacuum affects concrete during the hardening process and lowers its quality.

PROPOSAL FOR THE NEW PRODUCTION METHOD OF CONCRETE ON THE MOON

It is necessary to make use of the Moon's natural environment in order to utilize concrete for the construction of various structures. However, with the results from the prior section, concrete containing moisture and air should not be exposed to vacuum unless hydration of concrete proceeds up to a certain point. The lunar concrete method proposes a possible process under the natural environment of the Moon.

Outline of the Lunar Concrete Method

The production process would be as follows:

1. Water or cement paste is frozen to be powdered ice within an airtight chamber. If the lunar environment is utilized, special equipment would not be needed. Powdered ice is produced by spraying water or cement paste inside a cold chamber or onto the surface of a cold metallic board.

2. The concrete's structural materials, such as cement, aggregate, and powdered ice, are mixed under low temperature and vacuum. Since all materials are solid particles, a uniform concrete mixture is easily produced. Besides, mixture of concrete is easily handled under vacuum because the water vapor pressure of ice at low temperature is very low.

3. The concrete mixture at low temperature is transported and placed in a prescribed location. The temperature of the concrete should not be excessively raised when the concrete mixture is transported and placed.

4. The placed concrete is covered with airtight material and is thawed with energy applied from the outside. At the same time, the concrete is compacted with applied vibration and pressure. Microwave is considered as an external energy. The concrete is covered with airtight material for thawing and prevention of water evaporation.

5. The concrete is used as a structural material after having been cured for a predetermined period. A heat insulator is used for curing in order to control the maximum and minimum temperature of the concrete. After the concrete is hardened to a certain extent, the airtight material is removed from the concrete and the concrete is exposed to vacuum.

An Examination of the Lunar Concrete Method

As the first stage of examining the possibility of the lunar concrete method, an experiment with the use of mortar was performed as follows: (1) The mortar mixture is produced from

powdered ice, cement, and fine aggregates; (2) The mortar mixture is packed in an acrylic mold ($4 \times 4 \times 16$ cm); (3) Microwave is applied to the mold around a circumference to thaw the mortar mixture in the mold, during which the mortar is compressed several times to compact it; and (4) After it is cured in water at 20°C for 28 days, the mortar specimen's unit weight, flexural strength, compressive strength, and dynamic modulus of elasticity are measured.

The mortar's water/cement ratios were 35%, 50%, and 65%, with s/c = 2 and the use of high-early-strength portland cement. A domestic microwave oven was used to irradiate the specimens.

The results of the experiment are the following:

1. Powdered ice, cement, and fine aggregates had high dispersion since those materials did not have any adhesion. Therefore, the mortar was well mixed. Also, powdered ice in mortar was uniformly thawed by microwave. However, it became clear that final compacting is needed during or after thawing the powdered ice because the specimen's volume was reduced by thawing.

2. The ratios of the properties of the standard specimen to the mortar specimen (MW specimen) produced with the use of powdered ice and microwave are shown in Fig. 4. When the water/cement ratio is 65%, the MW specimen has quality for practical use since significant reduction in physical property figures, except for compressive strength, could not be found.

However, as the water/cement ratio got lower, those ratios became smaller. Void ratios of each MW specimen were calculated by mixing measured unit weight and mortar. They were 11% with a 35% water/cement ratio, 7.1% with a 50% water/cement ratio, and 5.0% with a 65% water/cement ratio. From these results, reduction in physical properties is considered to be caused by lack of setting.

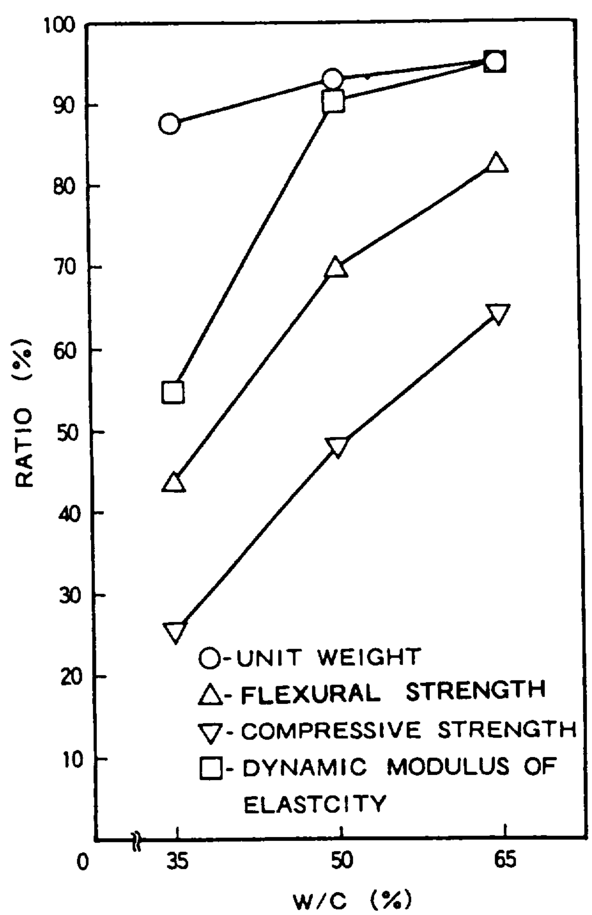


Fig. 4 The ratios of the properties of a standard specimen to the mortar specimen (MW specimen) produced with the use of powdered ice and microwave.

Features of the Lunar Concrete Method

The advantages of this method are (1) most of the manufacturing processes can be performed under the natural environment of the Moon; (2) an unnecessary amount of water is not used since ice can be equally dispersed into concrete, so the water/cement ratio can be relatively low, and especially when the cement paste in the state of powdered ice is used, the quality of cement is easily maintained because all cement particles hydrate within the concrete; (3) only the vapor, which is generated by heating ice, exists within the concrete mixture, so compacting concrete under vacuum is easier than in atmosphere; (4) given energy in the form of microwaves, the whole concrete mass is uniformly heated so partial strain accompanying thawing is hardly generated; and (5) concrete mixture in the solid-phase state influences the facilities for mixing, transporting, and placing concrete, which enables a reduction of labor in security and cleaning of those facilities.

Possibilities of basic technology for this method are confirmed to some extent. Nevertheless, immediate problems to be solved are (1) examination of the method of compacting and (2) verification of concrete production under vacuum. In the future, technological problems of the energy production process will have to be examined in detail.

CONCLUSION

The construction of a lunar city has to be planned by taking careful account of the natural environment, precious material, and human energy. Several possible methods of concrete production on the Moon are shown below.

1. When concrete is used for important structural members, a precast concrete panel is produced in the pressure chamber. At the time of production, pressure in the chamber should not be less than saturated water vapor pressure at curing temperature. Therefore 1-atm pressure need not be maintained within the chamber.

2. When concrete is used for less important structural members, precast concrete should be produced under the natural environment of the Moon by curing lunar concrete in a closed pressure vessel.

3. When concrete is used as a nonbearing member, it may be produced under the natural environment of the Moon. However, the concrete's surface should be covered with airtight material in which the concrete will be cured.

An experimental verification of concrete production under vacuum with these methods is a major subject in the near future. Besides, appropriate 'echnology has be to improved to provide sufficient performance or efficiency for structural materials.

CONCRETE STRUCTURE CONSTRUCTION ON THE MOON

N93-1 989

Shinji Matsumoto, Haruyuki Namba, Yoshiro Kai, and Tetsuji Yoshida

Shimizu Corporation
No. 4-17
Etchujima 3-chome
Koto-ku
Tokyo 135
Japan

This paper describes a precast prestressed concrete structure system on the Moon and erection methods for this system. The horizontal section of the structural module is hexagonal so that various layouts of the modules are possible by connecting the adjacent modules to each other. For erection of the modules, specially designed mobile cranes are used.

INTRODUCTION

A habitable structure in space must be designed to resist internal pressure. One current plan proposes that a large lunar structure can be constructed by connecting metallic modules. However, the plan restricts the size of each room so that the size of the module is not excessive. To illustrate, in a structure such as a dome providing large living space, if the dome is subjected to one internal atmospheric pressure it will develop very high membrane stresses that exceed the strength of existing material. Therefore, design of such a dome would be difficult.

This paper presents a new concept on module construction for spacious structures. The modules would be made with frames and detachable panels. This concept can be applied to any type of habitable structure in space, including concrete habitable structures on the Moon. The use of a standardized frame and panels permits easy assembly and the creation of large spaces. An artist's conception of a concrete structure lunar base is shown in Fig. 1.

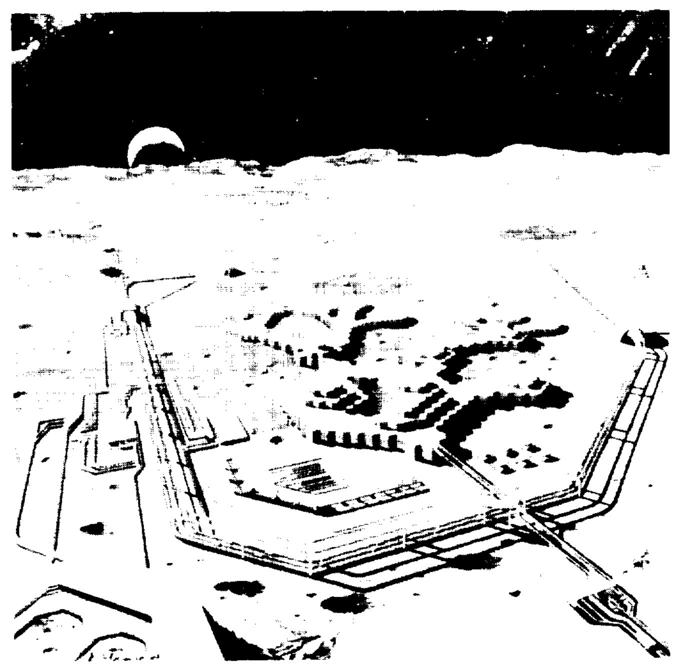


Fig. 1. Image of concrete structure lunar base.

PRIOR CONDITIONS

Certain conditions must exist prior to the feasibility of this system. (1) The technology to produce concrete from regolith must be established on the Moon; and (2) an Earth-to-Moon transportation system must be fully activated to provide the required materials (e.g., hydrogen) to the Moon from the Earth.

CONFIGURATION OF THE MODULE

Figures 2 and 3 show the shapes and sizes of the proposed modules. The net floor area of a module is approximately 15 sq m. The size of a module was determined according to the weight of the unit and the strength of the cables that are used for post-tensioning the modules together.

In order to pressurize the inner air of the module, a precast prestressed concrete structure is used. The frames are prestressed by post-tensioning at the lunar module manufacturing plant, and the joints of the modules are also post-tensioned on site.

COMBINATION OF MODULES

When several modules are combined and panels between contiguous modules are detached, a continuous large space can be created. A large number of modules of specific functions can be put together to form one large unit. The design must consider the architectural layout and usable area. One such layout of modules for habitation, research, and experiments is shown in Fig. 4. The entire structure is divided into three compartments: a habitation zone, a research zone, and a passage zone.

Since the size of the modules and the installation of equipment would be standardized, the structure could be easily modified in case the need for changes in layout arises in the future.

AN APPLICATION FOR A LARGE-SPACE STRUCTURE

Although the basic idea for space (room) expansion is to remove panels between contiguous modules, larger space could be ensured if more modules are added and if interior modules themselves are removed instead of panels between them (see

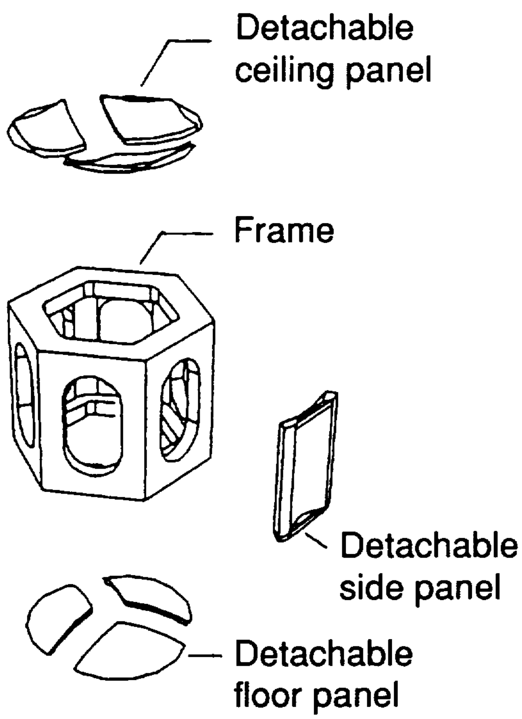


Fig. 2. Configuration of the module.

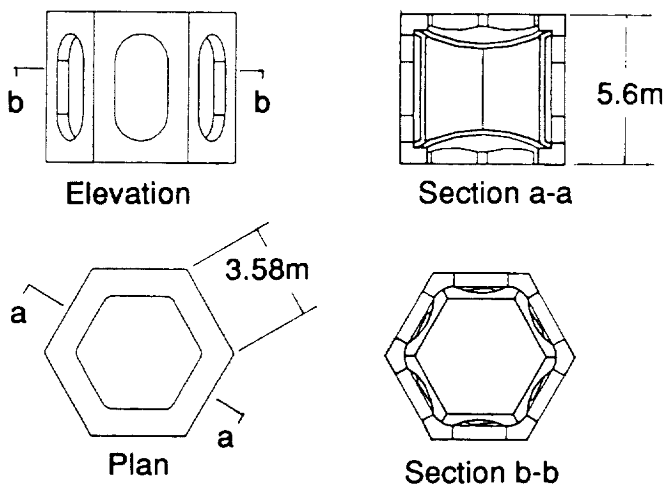


Fig. 3. Size of the module.

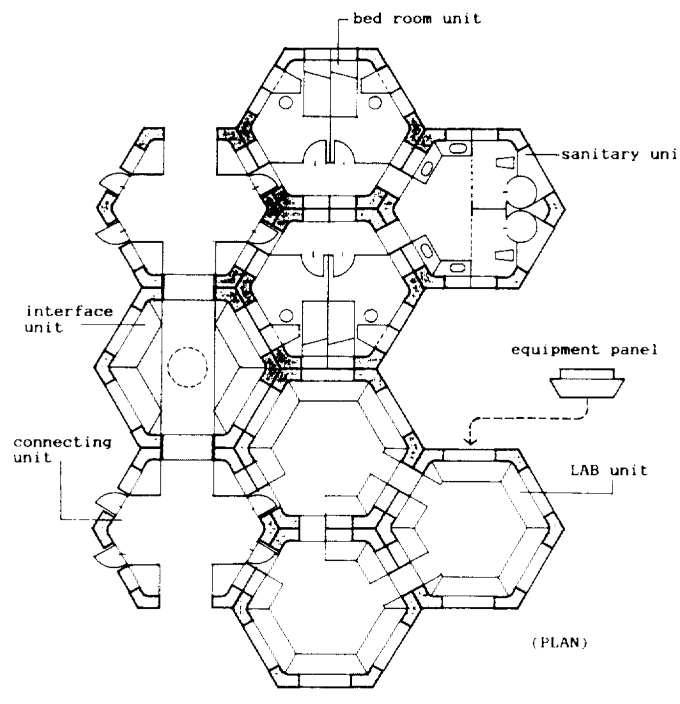


Fig. 4. An example of the module layout (equipped with habitation, research, and experiment facilities).

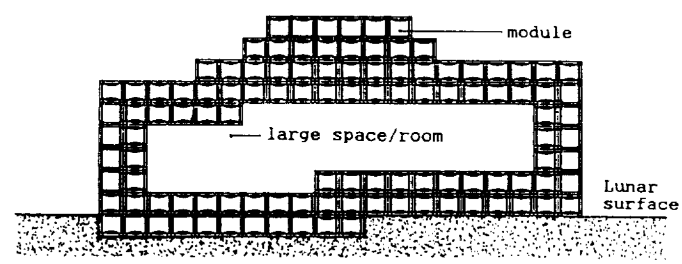


Fig. 5. Creation of large space/room by modules.

Fig. 5). Corresponding to requirements, pillars would be placed to bear tensile forces. As the weight of the accumulated modules constituting the roof increases, a large space without pillars could be created by balancing the weight of the modules against the internal air pressure. Of course, the roof structure should be designed to resist its own dead load and any live load, even if a loss of internal pressure should occur.

PRODUCTION PROCESS OF THE MODULES

Concrete production technology on the Moon is one of the necessary prior conditions. Figure 6 shows a flow chart that explains the production process. A module manufacturing plant needs a power plant, a cement plant, a prestressed material plant, and a water plant. At the module factory, concrete will be mixed and cast. After casting, the prestressing cables will be post-tensioned and the modules will be assembled. Finally, the internally pressurized modules will be shipped from the plant. The holes for inserting prestressed material are made by placing tubes in the mold before the concrete is cast. After the concrete hardens, the module is prestressed by the post-tensioning method.

Since the air pressure required for casting concrete does not have to be one atmospheric pressure, the air pressure in the plant could be relatively lower. Therefore, the module manufacturing plant can be a dome-like structure with a large space inside and the frame of the module can be integrated in the plant.

CONSTRUCTION PROCESS

Modules produced at the plant on the Moon are transported to the construction site. One module would weigh 30 tons on the Moon. Since the modules have to be plied between the plant and the construction site several times, and weak regolith stratum exists on the lunar surface, the use of self-propelled vehicles is inappropriate for module delivery. Therefore, a transportation

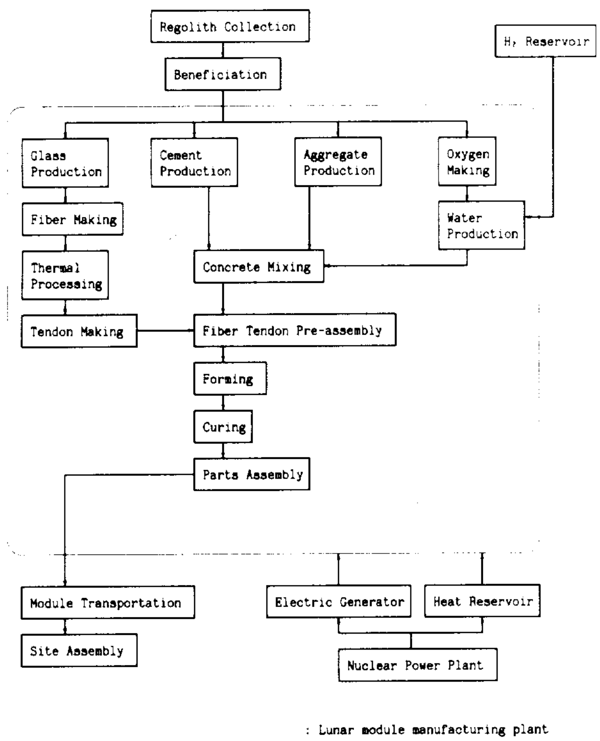


Fig. 6. The lunar module manufacturing plant and other necessary factories.

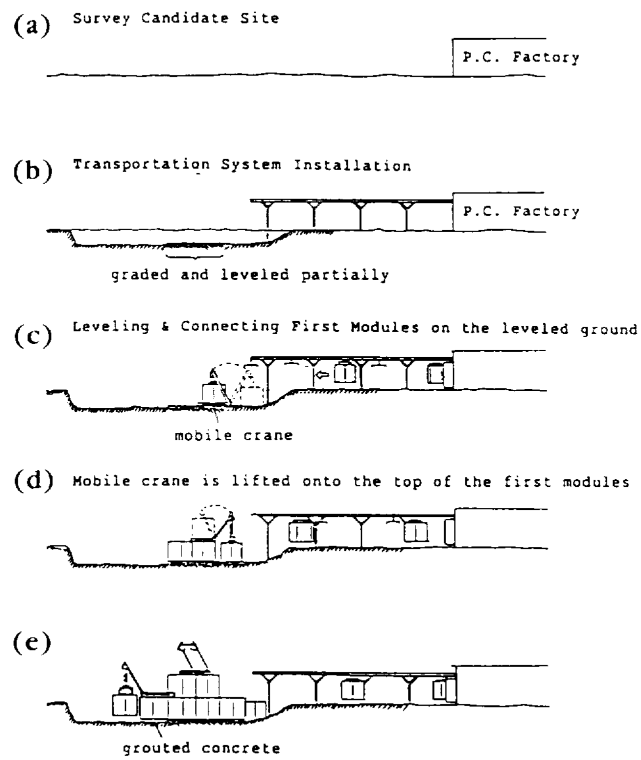


Fig. 7. Construction process.

system for delivery will be established to link the construction site with the plant. It is preferable that the construction site be as close as possible to the plant. In addition, the site should be on stable ground, which can be found by excavation of the thin regolith stratum.

The construction process is shown in Fig. 7. First of all, the transportation system is installed and the surface of the Moon where the first several modules are to be must be leveled (Figs. 7a,b). Second, the modules are transported to the leveled ground and a structure that consists of several modules is completed (Figs. 7c,d). By using the roof of the completed structure as the base, additonal modules are placed one by one. At that time, additional modules to be placed are temporarily supported as a cantilever attached to previously placed modules and the gap between those additonal modules and the ground is grouted with concrete (Figs. 7d,e). Therefore, the ground where the modules are placed need not be completely leveled. Prior to the grouting process, an inflatable stopper is placed under the module edge as an isolator.

OPERATION UNDER A PRESSURIZED ENVIRONMENT

Since the modules are pressurized before leaving the factory, a construction operator can work inside the module without wearing a spacesuit.

Figure 8 circumstantially explains how an additional module is installed. Horizontal cables on the top and bottom of the modules are tightened to support additional modules as a cantilever at-

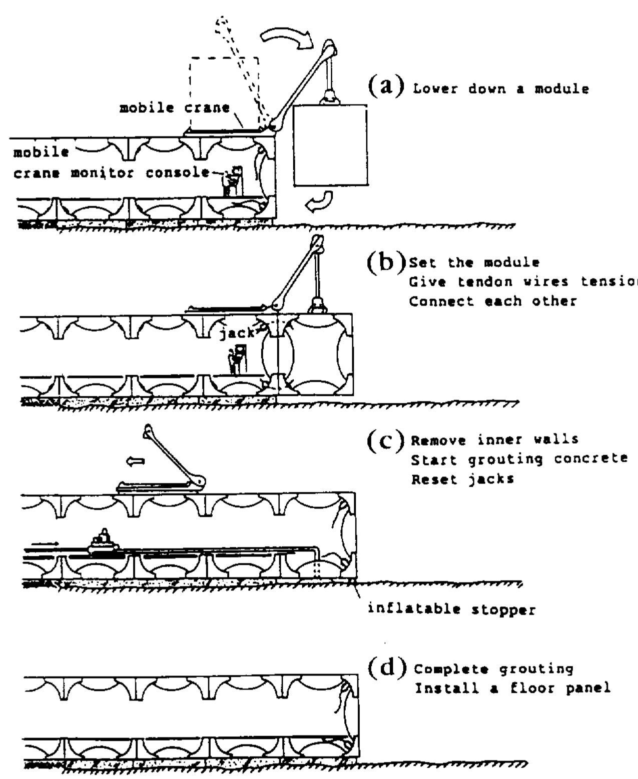


Fig. 8. Docking process under pressurized environment.

tached to the executed modules. Tightening of the cables can also be done under a pressurized environment if the dead end of the cable can be fixed by a specially designed latching system. Moreover, after removing the side panel between an additional module and an executed module, the operator can grout the gap between the additional module and the ground under a pressurized environment. The construction process will be efficiently and consistently performed under a pressurized environment.

CONCLUSION

The proposed lunar habitable structure has been examined in terms of architectural and structural design, manufacturing, and construction. The distinctive features of the structure are as follows:

1. The module consists of the frame and detachable panels. A contiguous large space will be gained by removing panels between two modules that are connected.

2. The configuration of the module is determined by the method of tightening parts with cables. Concrete is considered to be the most appropriate material for the module construction.

3. The method whereby a large number of modules is used to create a large space simplifies the architectural zoning decisions. In addition, the standardization of the interior parts of the module easily accommodates changes in the module and extension work in the future.

4. The frame of the module will be cast on site to simplify the construction process and to provide airtightness to the module.

5. Erection of the modules is carried out one after another using mobile cranes.

6. Connecting joints and grouting gaps can be performed under a pressurized environment.

LUNAR CONCRETE FOR CONSTRUCTION

Hatice S. Cullingford

Lunar and Mars Exploration Program Office
Code XE
NASA Johnson Space Center
Houston TX 77058

N93-18990

M. Dean Keller

Los Alamos National Laboratory
Los Alamos NM 87545

Feasibility of using concrete for lunar base construction has been discussed recently without relevant data for the effects of vacuum on concrete. Our experimental studies performed earlier at Los Alamos have shown that concrete is stable in vacuum with no deterioration of its quality as measured by the compressive strength. Various considerations of using concrete successfully on the Moon are provided in this paper, along with specific conclusions from the existing database.

INTRODUCTION

Concrete is probably the most widely used of all the man-made materials of construction. Its properties are (1) it does not require expensive, high-temperature, shape-forming processes; (2) it develops its strength at ambient temperatures; (3) it has low density and high thermal and electrical insulation properties; and (4) it is noncombustible and generally nontoxic (*Double,* 1981). Based on a historically long successful experience with concrete, it is natural that lunar applications have been suggested by *Lin* (1985) and others.

Concrete is by definition a polyphase material that consists of particles of aggregate connected by a matrix of hardened cement (*Lott and Kesler,* 1967). According to a scenario proposed by *Lin* (1985), cement could be obtained by high-temperature processing of lunar rocks, while aggregates would be obtained by physical processing of lunar rocks and soils.

The purpose of this paper is to discuss the authors' experimental work with concrete as it relates to lunar base construction.

NOVEL TESTING PROGRAM

Very little information exists in the vacuum or concrete literature on the behavior of concrete in vacuum, even though there has been a continued interest over the years in using concrete for vacuum applications. On the other hand, the stability of concrete in vacuum is intuitively questioned without data (*Cullingford and Fox,* 1980). Because there was a need to know the effect of vacuum on concrete's strength for a linear-accelerator line at the Los Alamos National Laboratory (LANL), we designed a test program to investigate both outgassing and compressive strength of concrete in high vacuum (*Cullingford et al.,* 1982a,b).

Outgassing characteristics of vacuum materials are typically reported in the vacuum science literature. Our study of concrete, however, involved a multidisciplinary treatment with an engineering approach to the problem of concrete's behavior in vacuum. To begin with, all concrete used was prepared as a mix, given in Table 1; the local aggregate with the composition shown in Table 2 came from the San Ildefonso Pueblo. Relevant engineering standards were applied for concrete preparation, curing, and

TABLE 1. Concrete design mix.

Material	Mass (lb)	Percentage (%)
Water	2.0	7.05
Portland Cement	4.1	14.47
Fine Aggregate	9.00	31.54
Coarse Aggregate	13.3	46.94
Total	28.3	100.00

TABLE 2. Composition of local aggregate.

	Fine Aggregate	0.25-0.75 in	0.75-1.50 in
Quartzite	2	45	36
Acid Volcanic	16	28	23
Granite	10	13	22
Basic Volcanic	1	8	11
Quartz	57	4	7
Feldspar*	9	—	—
Chert†	3	—	—
Residue	2	2	1
Total	100	100	100

where

	Granite	Basic Volcanic	Acid Volcanic	Quartzite
SiO_2	77.0	49.1	75.6	97.05
Al_2O_3	12.0	15.7	12.7	1.39
Fe_2O_3	0.8	5.4	1.2	1.25
FeO	0.9	6.4	0.34	—
MgO	—	6.2	0.12	0.13
CaO	0.8	9.0	0.59	0.18
Na_2O	3.2	3.1	4.0	—
K_2O	4.9	1.5	4.6	—
H_2O	0.3	1.6	0.46	—
Other	0.1	2.0	0.39	—

* Feldspar is assumed to be 50% $KAlSi_3O_8$ and 50% $NaAlSi_3O_8$.
† Chert is predominately SiO_2.

testing (*Cullingford et al.*, 1982a,b). Concrete samples thus prepared (cylinders of 6-in diameter by 12-in height) were designated by "test" or "control." The test cylinders were placed in high-vacuum environment for specified periods of time after air curing, while the control cylinders were not.

Figure 1 shows the experimental vacuum apparatus for the outgassing studies. The clean-system base pressure was 3×10^{-6} torr (3.99×10^{-4} Pa) after 160 hr pumping time. The test program involved a progression of air curing, weighing, vacuum treatment, weighing, and then breaking for compressive strength as represented in Fig. 2. All tests involved multiple cylinders for a more representative average behavior. This is an important point because of the inhomogenous nature of concrete.

Mass loss, compressive strength, and outgassing measurements were made during the test program. An increase in compressive strength with time is observed, reaching an equilibrium value of 6500 psi with or without vacuum exposure (*Cullingford et al.*, 1982a,b; Fig. 3). The significance of this result is that structures for vacuum use can be designed without additional safety margins.

The predominant pumped species in concrete outgassing was not a diatomic gas, but water vapor as studied by mass spectrogram of the residual gas in the test chamber (*Cullingford et al.*, 1982a,b). During the first several days of pumping, the outgassing rate was approximately 10^{-6} torr · l/cm^2 · sec. The empty chamber throughput at this time was about 3 orders of magnitude lower than the gross throughput with concrete samples in the chamber.

The mass-loss information was reduced to water content as percent of concrete dry mass and is also plotted in Fig. 3. Concrete became stronger as it aged. As expected, a faster drying rate was observed under vacuum exposure. A final water content of 6.6% and 4.93% was calculated on a dry-mass basis for the control and test samples, respectively. The total amount of water lost from the concrete cylinders was 0.13 and 0.35 lb_m/ft^2 for control and test cylinders, respectively. Thus, about 2.7 times the mass of water was released overall under vacuum treatment, without a reduction in compressive strength. The next section discusses further the effect of vacuum on concrete's water.

VACUUM EFFECT ON CONCRETE'S WATER

Water is present in concrete in three states: chemically bonded water in the hydration product, adsorbed water on the surface of gel particles, and condensed water in the capillary pores. When water is added to a mixture of Portland cement and aggregate to prepare concrete, hydration reactions occur between calcium silicates and the water. This hydration process continues for several days, and the concrete becomes stronger and harder. The drying phase during the air cure involves release of the free (not chemically bound) water from the concrete (*Lott and Kesler*, 1967).

Our data show that vacuum exposure produced faster release of this free water from the concrete samples. However, the fact that compressive strength does not worsen under vacuum treatment suggests that cement dehydration reactions do not occur. In addition, a constant rate of moisture loss (0.04% per day) was experienced during the early part of vacuum exposure, regardless of the length of the preceeding air-curing period (see Fig. 3).

The water evaporation rate corresponding to this constant rate of evaporation under vacuum is 3.97×10^{-8} g/sec·cm^2. On the other hand, the control samples underwent an evaporation rate of 0.92×10^{-8} g/sec·cm^2. These rates were compared with the calculated rate of free evaporation of water at the test conditions, using the following equation derived from the kinetic theory of gases (*Roth*, 1976; *Kaldis*, 1980)

$$W = 5.83 \times 10^{-2}\, \alpha\, P_v\, (M/T)^{-1/2}$$

where W is the rate of evaporation (g/sec·cm^2), α is the evaporation coefficient (1.0 for free evaporation), P_v is the saturation vapor pressure (torr), M is the molecular weight, and T is the surface temperature (K). This comparison showed that an evaporation coefficient of 1.59×10^{-7} is attributable to the vacuum's effect on concrete.

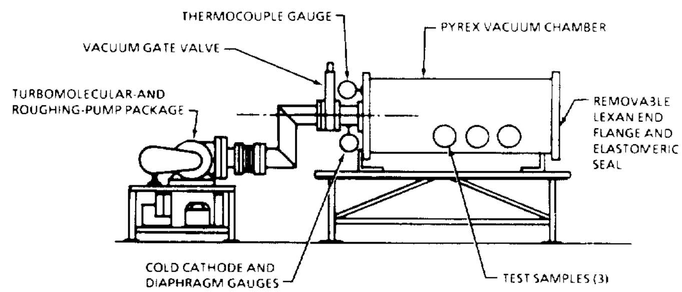


Fig. 1. Layout of vacuum pumping chamber for concrete samples.

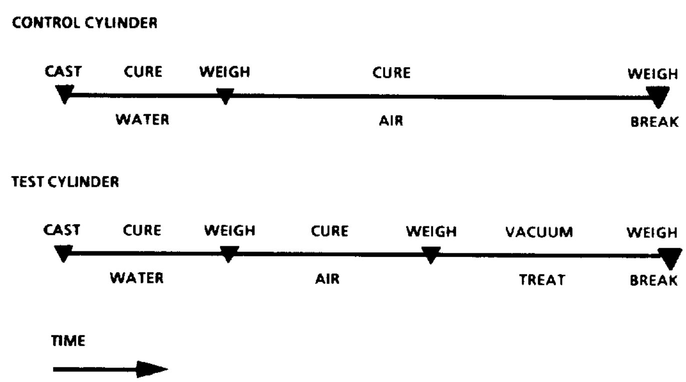


Fig. 2. Sequence of testing for typical control (air cured) and test (vacuum treated) cylinders.

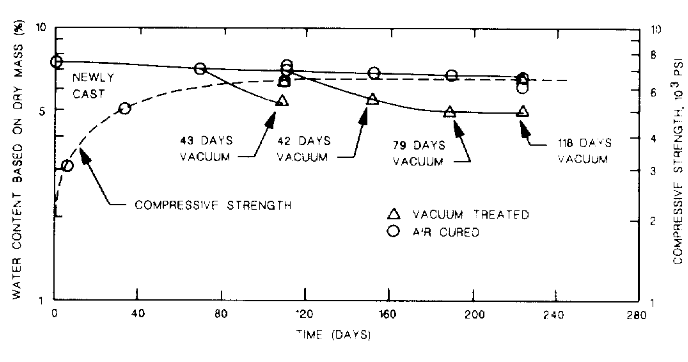


Fig. 3. Water content of concrete based on dry mass and compressive strength for air-cured and vacuum-treated cylinders.

Finally, the evaporation rates calculated for concrete in air or vacuum (in the order of 10^{-8} g/sec·cm^2) suggest a small surface cooling, and thus little uncertainty in the surface temperature of concrete (*Kaldis,* 1980). This assures a higher confidence in the constant-temperature analysis of the concrete data.

DISCUSSION

The experimental data obtained on concrete at Los Alamos are significant in planning for lunar construction with concrete. Several specific conclusions can be derived from our study.

1. Concrete is stable in vacuum with no deterioration of concrete quality as measured by compressive strength (ours was about 6500 psi).

2. Water loss from the concrete cylinders was 0.13 and 0.35 lb_m/ft^2 for control (without vacuum exposure) and for test (with vacuum exposure) samples, respectively.

3. An evaporation coefficient of $1.59 \cdot 10^{-7}$ is attributable to the vacuum's effect on concrete during constant rate of drying.

4. An outgassing rate of 10^{-6} torr · l/cm^2 · sec was observed after 73 hr of vacuum pumping. The predominant gas species was water vapor.

5. A high vacuum of 2×10^{-4} torr was maintained with the mechanical pumping system used in the experimental apparatus.

Using concrete on the Moon requires, however, various considerations like those discussed below.

The Moon gravitation is less than that of the Earth; therefore, concrete would be better able to handle stresses of large structures. However, the forces would not always be acting in the ways to which we are accustomed.

Any dome structure on the Moon would probably have pressure on the inside and vacuum on the outside. The dome would therefore have to act in tension. However, concrete is weak in tension. Reinforcing would then require the manufacture of steel on the Moon or shipment of steel to the Moon. Fiber reinforcing, especially of a type that could be manufactured locally, would aid in providing tensile strength for concrete.

Assume the pressure inside a dome is about 10 psia. This would require 1440 psf of pressure exterior to the dome to resist by "dead weight." With the Moon's gravity as it is, this would be a high backfill over the dome. The anchoring problem around the perimeter would have to be solved. Another possibility would be an excavated underground volume with lined walls. This would offer protection from meteoroids that do not burn up due to lack of atmosphere. A combination of cement, lunar rocks and soils, and fiber reinforcing could provide a coating on walls for protection against rock slides.

To construct various concrete shapes at entrances and shafts, preplaced aggregate could be formed and a grout pumped into the voids. Consideration would have to be given to concrete shapes to assure that the low lunar gravity and the internal pressure are acting to place the concrete in compression. Form enclosures would have to be airtight to assure that water is not lost before the hydration process is complete. Vacuum would then be directed so that moisture could be captured when it is withdrawn from the hardened concrete.

Concrete can be formed by using an air-filled dome. For example, if two domes are constructed with one bag placed within another so that they are concentric and separated by about 2 ft, the interior air bag could be inflated to about 10 psia with the differential between the inner and the outer bag being about 2 psia. Straps could be used so that the bags will always remain separated by about 2 ft. Concrete can then be placed in the annulus between the two bags. Concrete operations can be carried out within the inner bag, while the lunar aggregate is also mined inside the bag. The water needed could be also manufactured inside. Problems to solve include the breaking of the bag material by penetration of flying objects and the anchoring necessary at the perimeter. The bags could be fabricated on Earth complete with a floor and a number of airlocks already formed in the walls of the bag. The air bags would then supply the tensile strength. The concrete cast within the annulus would provide resistance to penetration and radiation protection.

We don't know how firm the rock structure is on the Moon, or how deep the loose top material is. Unless an enclosed tube is constructed with pressure in all directions (thereby eliminating any vector forces in the vertical direction), we could look forward to being forced to remain deep below ground. Air bags, in concert with concrete, could provide us with a viable alternative for a stable above-ground structure. Alternative geometric shapes and sizes of the air bags would have to be carefully studied.

CONCLUSION

The experimental data discussed in this paper are significant for lunar base construction with concrete. Having studied the effect of vacuum on concrete, we find that additional safety margins are not needed for vacuum use. Our recommendation is to focus future inquiry on developing structural options with concrete for lunar habitation.

Acknowledgments. This work was originally supported by the U.S. Department of Energy. The help received from The Zia Company, Los Alamos, New Mexico, is appreciated by the authors. R. W. Higgins of the LANL was a team member of this experimental effort. W. E. Fox, also of the LANL, first brought up the problem of vacuum's effect on concrete's strength to H. S. Cullingford who later led this work.

REFERENCES

Cullingford H. S. and Fox W. E. (1980) In *Proc. 16th Annual Symposium, American Vacuum Society,* New Mexico Chapter, Santa Fe.

Cullingford H. S., Keller M. D., and Higgins R. W. (1982a) Comprehensive strength and outgassing characteristics of concrete for large vacuum system construction. *J. Vac. Sci. Technol., 20,* 1043-1047.

Cullingford H. S., Keller M. D., and Higgins R. W. (1982b) Behavior of concrete in vacuum environment. Am. Inst. of Chem. Eng. Annual Meeting, Annaheim, California.

Double D. D. (1981) Cement—A respectable material? *Nature, 289,* 348.

Kaldis E., ed. (1980) *Curr. Top. Mater. Sci., 5.* North-Holland, New York.

Lin T. D. (1985) Concrete for lunar base construction. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 381-390. Lunar and Planetary Institute, Houston.

Lott J. L. and Kesler C. E. (1967) *Mater. Res. Stand,* p. 375.

Roth A. (1976) *Vacuum Technology.* North-Holland, New York.

6 / *Life Support and Crew Health at a Lunar Base*

THE ENVIRONMENTAL CONTROL AND LIFE-SUPPORT SYSTEM FOR A LUNAR BASE— WHAT DRIVES ITS DESIGN

N93-13991

Warren D. Hypes

Consultant
Bionetics Corporation
Hampton VA 23665

John B. Hall Jr.

NASA Langley Research Center
Hampton VA 23665-5225

INTRODUCTION

What is the likely design of an environmental control and life-support (ECLS) system that initially supports 4 crewmen during intermittent 10-day periods and ultimately supports 20 to 50 crewmen on a permanent basis? How much does it weigh, and what is its size (or volume)? The first question is ambiguous and unanswerable. The second is more specific but equally unanswerable until the mission ground rules are specified and until more information is given on systems other than the ECLS system and on the operational scenario of the base. Once specified, ground rules often become early absolute design drivers that negate some of the trade-offs of options, whereas details of other base systems and the base operational scenario often become design drivers that support and focus trade-offs between technology options. The purpose of this paper is to identify and briefly discuss some of the ground rules and mission scenario details that become drivers of the ECLS system design and of the logistics related to the design.

This paper is written for mission planners and non-ECLS system engineers to inform them of the details that will be important to the ECLS engineer when the design phase is reached. In addition, the examples illustrate the impact of some selected mission characteristics on the logistics associated with ECLS systems. The last section of this paper focuses on the ECLS system technology development sequence and highlights specific portions that need emphasis.

FACTORS THAT DRIVE SYSTEM SELECTION

As stated in the introduction, some ground rules become absolute design drivers that negate additional trade-offs. Since their impact is absolute, they will be discussed first.

Life-Cycle Costs vs. Initial Costs

The selection of either life-cycle costs or initial costs as a ground rule, coupled with the mission duration and crew size, becomes an absolute driver relative to the first-order design decision, i.e., to carry only expendables (nonregenerative system) or to reclaim usable products from wastes (regenerative system). The terms nonregenerative and regenerative will be used in this paper rather than open and closed, because they are more technically correct. Seldom will any ECLS system loop be totally closed.

Table 1 presents a highly simplified summary of the relationship between mission cost elements, mission duration, and the type of ECLS system. As shown in the table, the regenerative ECLS system is the only viable candidate for long-duration missions when life-cycle costs dominate. A permanently manned lunar base is certainly a long-duration mission, and it would be folly to adopt any costs other than life-cycle costs to dominate design studies. This particular discussion topic could end here, since only one option is viable for a manned lunar base; however, it appears prudent to explain the elements of Table 1 to clarify the rationale.

The terms short-, medium-, and long-duration missions are relative. Certainly the space shuttle missions of 7 to 10 days are short missions, and the ECLS system is nonregenerative. Certainly a permanent manned lunar base with years of occupancy is a long-duration mission. A medium-duration mission is difficult to define, but 30 to 90 days is reasonable.

The cost terms have been defined by *Hall et al.* (1985) relative to their use in ECLS system studies. The initial cost includes the cost to design, develop, test, and evaluate (DDT&E) the first flight model; the cost of the flight-unit spares and consumables for the initial launch; the ECLS system integration costs; and the programmatic costs. Life-cycle costs include the initial costs plus the operational costs. Operational costs include the cost of spares and consumables to operate over the mission duration; transportation costs of the spares and consumables; transportation costs of the initial flight units; and maintenance costs for the mission.

For long-duration missions, the operational costs are the drivers. Nonregenerative ECLS systems feature low DDT&E and flight unit costs, very high operational costs due to the transportation costs of the spares and consumables, and resulting very high life-cycle

TABLE 1. The applicability of nonregenerative and regenerative ECLS systems relative to initial and life-cycle costs.

	Initial Costs Dominant	Life-Cycle Costs Dominant
Short-Duration Missions	Nonregenerative	Nonregenerative
Medium-Duration Missions	Nonregenerative	Regenerative
Long-Duration Missions	Not applicable	Regenerative

costs over a lengthy mission duration. Regenerative ECLS systems feature opposite characteristics: high initial costs due primarily to expensive DDT&E costs, modest operational costs, and resulting lower life-cycle costs relative to those of nonregenerative systems.

To illustrate this discussion, a specific example has been extracted from *Hall et al.* (1985). Nonregenerative and regenerative techniques for removing CO_2 from the habitable environment and supplying O_2 to the environment of an Earth-orbiting space station were priced. The mission model included a crew of 6, a mission life of 10 yr, and a resupply period of 90 days. Table 2 presents the cost analysis. The accuracy of a cost analysis of this type depends on having access to factual flight costs and to the skill to which the ECLS system engineer can evaluate the DDT&E costs, spares required, maintenance costs, etc. It is obvious, however, from the example given in Table 2 that even if the cost analysis is not highly accurate, the difference between the operational and life-cycle costs of nonregenerative and regenerative systems is sufficiently large to mandate a regenerative approach. For missions of the type being proposed for early operational lunar bases, i.e., staffing at a level of 4 to 20 crew persons for multiple years, the technology of regenerative ECLS systems becomes an enabling technology.

TABLE 2. Cost analysis (in millions, 1984 dollars) for nonregenerative vs. regenerative CO_2 O_2 supply for a 10-year mission.

	Nonregenerative CO_2 Removal-LiOH* O_2 supply-stored	Regenerative CO_2 Removal-EDC† O_2 supply-Sabatier‡, SFWE§
Initial Cost	16.68	38.75
Operation Cost	783.83	129.35
Life-Cycle Cost	800.51	168.1

*LiOH-Lithium hydroxide.
†EDC-Electrochemical depolarized cell.
‡Sabatier-A CO_2 reduction reactor (to produce water).
§SFWE-Static feed water electrolysis (to produce oxygen).

Inheritance from an Earlier Program

One of the ground rules frequently used in lunar base mission studies is that systems (such as the ECLS system) to be used on the base will feature space station inheritance. This is a rational ground rule provided two assumptions are valid: an Earth-orbiting space station will precede the lunar base (highly likely), and the space station ECLS system is applicable to the lunar base (likely but not assured). If these two assumptions are valid, the ECLS system delivered to the Moon would be essentially "off-the-shelf" hardware resulting in high reliability at a modest initial cost. The second assumption, however, requires some discussion before being accepted as sacrosanct. The current space station reference configuration ECLS system features water reclamation and O_2 recovery subsystems. The water reclamation system is targeted for 95% to 97% water loop closure. If this target is met, the water reclamation system could well meet the needs of a lunar base. Tight schedules, limited funding, and any underestimate of the magnitude of the development effort required to advance the reclamation subsystem to the necessary maturity level could lead to a reduction in the water loop closure. The 95% to 97% closure requires reclamation of humidity condensate, wash and hygiene water, and urine. A decision to downgrade the reclamation subsystem to one, processing only humidity condensate by a simple filtration unit, would reduce water loop closure to the degree that it would no longer meet the needs of a lunar base. The same situation exists with the O_2 reclamation subsystem. The current space station baseline ECLS system includes an O_2 reclamation subsystem featuring a regenerable CO_2 concentrator, a CO_2 reduction reactor, and a water electrolysis unit to produce O_2. A fall-back position would be to retain the regenerable CO_2 concentrator, but drop the two units required to generate O_2. The Skylab spacecraft was flown in this configuration. Should the space station program make this decision, the lunar base ECLS system designer would need to add to the inherited baseline system. Inheriting an incomplete O_2 reclamation loop would not be as severe a problem as inheriting an incomplete water reclamation loop. The weight of O_2 needed is much less than the weight of water needed per unit of time. In addition, the quick achievement of a lunar LOX production facility (for propulsion use) would eliminate the need for an O_2 recovery loop in the ECLS system.

There is another important consideration relative to adopting a space station inheritance ground rule for the lunar base ECLS system. The inheritance ground rule would be most applicable to lunar base development scenarios that also inherit space station modules, a modular-type growth pattern, and a space station-type power system. The effect of these will be discussed in more detail in later portions of the paper.

A good way to conclude the discussion of a space station inheritance ground rule is to recommend an approach to lunar base program managers and ECLS system engineers. Space station inheritance is a good principle. It should be continually evaluated. It may result in the most reliability for the least cost; however, at this early stage in lunar base studies, it should not be accepted as a sacrosanct ground rule. It may lure the lunar base program manager into a feeling of false security, and the ECLS system may not meet the needs of the lunar base.

Self-Sufficient Base

The ground rule for a self-sufficient base is difficult to properly treat in a brief discussion. This ground rule extends beyond the ECLS system, but in this paper the discussion will be limited to its relationship to the ECLS system. Relative to the ECLS system, it is a ground rule that most likely cannot be achieved. Even the most optimistic projection of technology by *MacElroy and Klein* (1985) suggests a bioregenerative life-support system intended to recycle 97% of the mass that it contains. MacElroy and Klein state that some quantities of H_2, C, and N_2 will always be brought from Earth. The issue of N_2 logistics is discussed in detail later in this paper.

After accepting the fact that self-sufficiency within the ECLS system may not be achieveable, it is important to consider the intent of the ground rule and work toward this intent rather than the absolute definition of the term. The intent is to make the lunar base as autonomous as possible and to eliminate Earth-to-Moon logistics to the maximum possible extent. Within the ECLS system, this translates to keeping materials losses to the minimum, attempting to recover useful materials from every waste product, and increasing the closure of the food loop. The first two of these objectives are valid for all lunar base ECLS system designs, so the self-sufficient ground rule has little efffect on the design. Thus, the new factor that is introduced is the attempt to close the food loop. An attempt to close the food loop would be a major driver in the design of an ECLS system. Until the addition of food generation, lunar base ECLS systems will likely be based on physical and chemical processes. With the addition of food generation, bioregenerative processes will be added that may cause the physical and chemical processes to be modified.

Why not just include bioregenerative processes in the beginning? The technology is not ready for inclusion as a baseline. The processes are inefficient and high in energy demand. Early lunar bases may not be capable of meeting the demand. When these two limits are overcome, one more issue must be addressed. The total costs of including the "more closed food loop" must be traded off with the total costs of not including it. Total costs include many resources other than dollars: energy, space, crew time, monitoring, control equipment, etc. As long as the food that is carried from Earth is acceptable, there is no reason to attempt to generate it on the lunar base until it provides some type of payoff. When the technology for bioregenerative systems is established and mission trade-off studies conclude that it is time to integrate them into lunar base designs, it will become a major driver of the ECLS system.

FACTORS THAT DRIVE SUBSYSTEM SELECTION AND SYSTEM DESIGN

These factors are considered relative to a specific base design and development scenario. There is no priority betwen them. They each affect different elements of subsystem selection and system design.

Power Level and Type of Power System

The available power level could well be placed in the category of overpowering design drivers. Without adequate power, there can be little regeneration by the ECLS system. An overly generalized but true statement is that the more power available, the more regeneration can be accomplished and the more wastes can be processed to reduce weight, volume, and offensiveness.

In a recent in-house study conducted by the Spacecraft Analysis Branch (SAB) of the NASA Langley Research Center, a baseline regenerative ECLS system supporting a Phase II lunar base (four crew persons; intermittent operation) evolving into a Phase III lunar base (eight crew persons; continuous operation) was defined. The ECLS system included both water and O_2 recovery, whole-body bathing, clothes washing, solid-waste processing, and contaminant control. Thus, the proposed ECLS system was regenerative to the maximum degree short of attempting to generate food. This is the type of ECLS system most applicable to early continuously manned lunar bases. The electrical power requirements for the Phase II and Phase III ECLS systems were 10.5 kW and 21.2 kW, respectively. The requirements are misleading, however, if used at face value, because they are peak requirements and should not occur frequently. The average values should be significantly lower.

If mission planners and ECLS system engineers develop a base operational scenario that would time phase some of the ECLS system operation, the peak and the average power-use profiles could be lowered. Mission planners and ECLS system designers need to work closely to "smooth out" the utilization of the power resource while still providing optimum service.

Another qualification of the power values can be illustrated by using the Phase II ECLS system power level of 10.5 kW as an example. It would be a mistake to conclude that the required level of 10.5 kW is due primarily to the inclusion of a regenerative ECLS system. Only 34% of the 10.5 kW can be charged directly to regenerative subsystems or to subsystems that are available because regeneration is included, i.e., whole-body shower and washable clothing.

One technique used by the ECLS system engineers to trade off the impact of regeneration on the power system and to trade off candidate subsystems within the ECLS system relative to their power-use characteristics is the use of the power penalty factor. The power penalty will be stated as a finite number, for example, 250 lb/kW. For every kilowatt of power demand by the ECLS system, the power system weight would be increased by 250 lb. Thus, the 250 lb has to be charged to the ECLS subsystem to determine its equivalent weight. The power penalty is not determined by the ECLS system; it is determined by the state of the art in the design and development of power systems.

Another power system characteristic that may have a large impact as an ECLS system design driver for advanced lunar bases is the availability of excess heat, referred to as "waste heat," from the power system. It was previously stated that regenerative ECLS systems need power. More specifically, they require energy, and it can often be in the form of heat energy rather than electrical energy. The availability of waste heat delivered to the ECLS system through a high-temperature fluid can significantly reduce the electrical energy that would have been required to provide the heat by the use of electrical resistance heaters. Hot fluid loops can be used to raise bed temperatures of solid sorbers (silica gel, molecular sieves, activated carbon, etc.) that use heat and vacuum to desorb (regenerate) the solids. Temperatures in the range of 350°-400°F are satisfactory. Waste heat can also be used to provide energy for phase-change water reclamation subsystems (air evaporation and vapor diffusion). Lower temperatures in the range of 150°-180°F are adequate for these applications. Both of these temperature ranges can easily be obtained with nuclear power systems. Before waste heat is accepted as a panacea, however, the difficult tasks of delivery, control, and maintenance of a waste heat loop containing a hot fluid in the range of 350°-400°F must be engineered. At this date, the availability of waste heat and the practicality of its use appear to coincide with the development of a mature lunar base where a nuclear power system and the ECLS system can be integrated into a "city utility" concept.

The Gravity Factor

The lunar one-sixth gravity field is a design driver that is unique to a lunar base when compared with space systems that will have preceded the lunar base. This driver will have less impact if the previously discussed ground rule of space station inheritance is applied, because the design will have previously been established. A design developed for the space station will be tailored for zero-gravity operation. It should also be functional in the one-sixth gravity field, but it may be more complex than necessary for use on the Moon. If designed specifically for lunar base use, the ECLS system design could use the gravity field to aid in waste collection and transfer, liquid/gas phase separation, transfer of fluids, and in the use of personal hygiene facilities such as the whole-body shower. If inheritance of a space station zero-gravity functional ECLS system does not occur and the ECLS system is designed specifically for the lunar base gravity field, subsystem selections will change.

Base Layout and Composition

The base layout and composition are other design drivers that are unique to the lunar base ECLS system. With previous and current spacecraft systems, the ECLS systems have been centralized compact systems within a single pressurized vehicle. Even space

stations with multiple modules represent a more central core complex than possible lunar base layouts. With tight clustering, an ECLS system or subsystems supporting more than one habitat can be envisioned. As habitats spread away from each other, they will likely have to be self-contained. The mass flows of solids, liquids, and gases between the habitats and the processing subsystems are small. Lengthy plumbing lines would be incompatible with balancing the mass flows. Pumping would be an added problem. For the "city utility" ECLS system concept previously mentioned to be practical, the base must include a large crew providing a continuous large supply of wastes and using reclaimed material on a matching continuous basis. The flows need to be sufficiently large to prevent waste inputs or use of resources by a single individual habitat from significantly perturbing the flow.

The composition of the lunar base will also be an ECLS system design driver. Simultaneous operation of a continuously manned habitat area (with or without attached laboratories), a LOX production plant, a detached and remote observatory, a storage and maintenance shed, remote stations, etc., will undoubtedly impact ECLS system design. Separate ECLS systems of different types would probably be needed. For example, a continuously manned habitat cluster will require a more complex ECLS system (probably regenerative) than an observatory that is manned periodically (probably nonregenerative and containing fewer functions). Perhaps the most important part of this issue is yet to be resolved. What kind of internal environment do these "nonhabitat" facilities have to provide? Are they pressurized? Are we providing an environment for shirt-sleeve operation, or are we going to mantend these facilities with astronauts in pressure suits? What are the thermal control requirements for both the crew and the equipment? The answers to these questions may not be design drivers for the initial lunar base with a small crew and a tightly clustered habitat area; however, as the base expands into a complex habitat with lunar production and a scientific complex, base layout and composition will become major design drivers.

Use of the Lunar Environment

A decision that the lunar environment can or cannot be used in the operation of the ECLS system is a significant design driver, specifically in the selection of processes and subsystems to provide specific functions. The lunar environment offers unlimited hard vacuum, high and low temperatures, and potential waste disposal areas. Two of these, vacuum and high temperature, are commonplace in an ECLS system and are normally acquired at the cost of electrical power and additional hardware elements (vacuum pumps, heaters, blowers, etc.) If the lunar environment can be utilized, considerable savings in ECLS system weight, volume, and power could be realized. Two examples can be used to illustrate how the environment can be used. In an ECLS system that does not reclaim O_2 from CO_2, the CO_2 still must be removed from the habitable atmosphere. A leading candidate for this function is to use molecular sieves to selectively adsorb CO_2 from a cabin airstream. After the bed of molecular sieves is saturated with CO_2, it must be desorbed. This could easily be accomplished by venting the bed to the lunar vacuum. Another example is to use the lunar cold and vacuum to vacuum/freeze-dry wastes including human feces and miscellaneous garbage. The environment would then provide an ideal sterile storage for the processed waste material. A variation of this approach is to process the waste material in the habitat or other enclosed structure and expose the material to the lunar environment (disposal) only after it has been sterilized. Several possible approaches are available depending on how the lunar environment conditions are worked into the processing and storage scheme.

The opposite approach to the above is often suggested, i.e., no venting of gases to the environment or storage of wastes on or under the lunar surface. An absolute adherence to this position would be a significant ECLS system design driver. It would eliminate the use of all ECLS system processes that require venting to operate. It would add additional components to the molecular sieve CO_2 removal unit to store the desorbed CO_2 for return to Earth. It would also restrict the use of the Sabatier CO_2 reduction unit (which produces water) because it could no longer vent methane to the outside environment. As any one unit is eliminated, the effect may cascade throughout the subsystem because some of the units are practical only when integrated with other specific units *Quattrone* (1981). There are valid reasons for the approach of isolation between the lunar environment and the ECLS system; however, total isolation between the two will be technically difficult and practically impossible. Regardless of the ultimate decision on how the lunar environment can be used, the decision will become a design driver.

Intermittent or Continuous Occupancy

This mission operational feature may ultimately become one of the major design drivers. There are at least two entirely different types of impact that it may have on the ECLS system design. The first impact is to again raise the issue of nonregenerative vs. regenerative systems. For an intermittently occupied base, a likely scenario would be to include an air revitalization subsystem with a regenerable CO_2 removal unit, but without units for subsequent O_2 recovery. The ECLS system could also include a simple filtration-type water recovery unit for processing humidity condensate, but not include the more complex water recovery unit for processing wash water and urine.

The second type of impact relates to operation of the ECLS system. There are four problems with an intermittent operation scenario: complexity of startup and shutdown procedures, protection of the ECLS system during the down periods, matching of process flows with use rates, and maintenance of sterility of the process loops. The first three problem elements are readily apparent, but the fourth one needs some explanation. Testing experience to date with water recovery subsystems has repeatedly demonstrated that maintaining acceptable microbiological conditions throughout the entire water management subsystem (process unit, plumbing, storage tanks, etc.) is difficult. It is especially difficult during shutdown periods between operations. At many locations throughout the subsystem, there will be sufficient moisture and temperature to support microbial growth. The addition of waste waters with their inherent supply of nutrients then completes setting up the environment in which microbial growth can flourish. As was necessary during ground testing, each operational period may need to be initiated by a complete water management subsystem sterilization. The only completely satisfactory way to accomplish this during testing has been steam sterilization. Steam sterilization requires water, power, and subsystem components that are not damaged by steam. It also requires a subsystem design that accommodates the injection and passage of steam. The microbial problem associated with intermittent operation of water management subsystems will be a design driver in the selection of subsystems and in the operational scenarios. The problem may even preclude the use of complex,

regenerative water reclamation subsystems until the base is continuously manned and the water reclamation subsystem can be operated continuously in a mode that maintains an acceptable microbial profile.

Safety and Convenience of Operation and Maintenance

Up to this point in the discussion of factors that drive subsystem selection and system design, the factors discussed were those more associated with characteristics of the overall mission and systems other than the ECLS system. There are some important factors that are inherent within the candidate ECLS system processes and hardware configurations and have little to do with the overall mission characteristics. These factors could be discussed under numerous titles, but safety and convenience are certainly appropriate. No one takes exception to the statement that the ECLS system must be safe to operate and maintain. The difficulty is to define "safe" or its corollary, "unsafe." Many of the candidate processes involve producing and handling gases such as H_2, O_2, CH_4, CO_2, and NH_3. High-temperature fluids, including the previously mentioned steam and waste-heat fluid loops, may be present. High pressures are also possible. One advanced concept discussed by *Sedej* (1985) for combining functions of water reclamation and waste processing operates at a pressure of 250 atm and temperature of 670°F. This concept has great potential when the lunar base ECLS system advances to the "city utility" type of operation, but it is not likely to be factored into a habitat based on space station-type modules where the crew lives alongside the ECLS system. Safety considerations extend beyond normal operations into planned and unplanned maintenance. The hazard of "breaking into" or "opening" a process for maintenance can be a problem. Once beyond the safety issue, the next consideration is one of convenience and time. Crew time is a valuable commodity, and demand on crew time is certainly a driver in the selection and design of the ECLS system.

It was not intended in this paper to discuss all the trade-offs that occur within the ECLS discipline while arriving at a proposed design. The primary reasons for including this short discussion on safety and convenience are twofold. First, safety and convenience are important, and second, it is only fair to acknowledge that many of the design drivers are still under control of the ECLS system engineer rather than in the hands of the mission planner. The ECLS system engineer still has to advance process and hardware technology to the extent that advantageous concepts resulting in the most efficient mission scenarios can be incorporated into the designs in an operational mode that is within limits of safety and operational convenience.

FACTORS THAT IMPACT INITIAL LAUNCH AND RESUPPLY LOGISTICS

There is a group of factors that have little effect on ECLS system design and subsystem selection (once the decision to regenerate is made). They do, however, have a large effect on the final weight and volume totals for the initial launch and resupply logistics. They will be discussed separately, but in reality, their effects are interlocked.

Crew Size

The ECLS systems design engineers routinely work with crew needs and effluents in units of pounds per man-day. A typical needs/effluents mass balance is shown in Fig. 1. Each crewman

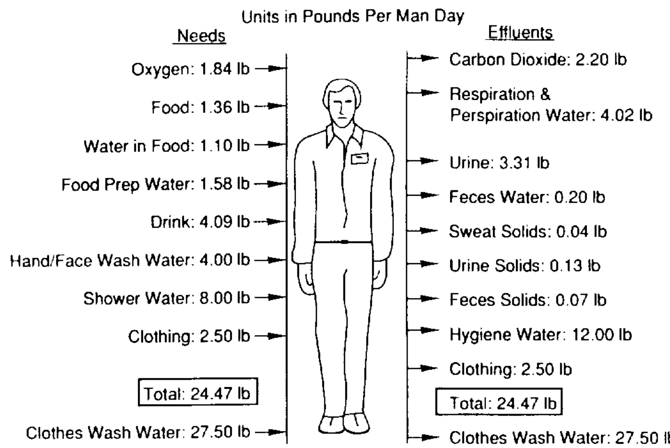


Fig. 1. Typical needs/effluents mass balance.

has to be supplied with 24.47 lb of supplies per day, and if clothing is washed, the number climbs to 51.97 lb of supplies per day. Current ECLS system technology and technology projected into the near future cannot close all the loops recycling useful materials from the effluents side of Fig. 1 back to the needs side. The O_2 requirement can be recovered from CO_2, although makeup O_2 will be required for leakage, air-lock losses, and emergency repressurizations. A large percentage of the total water needs (90% is a reasonable estimate) can be recovered. The food and food water will need to be transported from Earth. In addition to these expendables (total needs minus total regenerated), other expendables are present in food preparation items, waste handling packages, etc. The total weight and volume of the expendables that need to be launched and resupplied are then directly proportional to crew size and to the resupply interval.

There is another more subtle effect of crew size on ECLS system design. Subsystem developments during the past 25 years have evolved to a crew size of 4 as the target for full-scale models. A crew size of four is consistent with early space station crew size concepts and with individual modules of later, more advanced space station concepts. There is another reason, however, why the four-man-sized subsystem has persisted. It has proven to be a practical, convenient-sized unit to develop, test, and "handle." Process rates associated with four-man subsystems are in the general range of those "most easily controlled." Four-man-sized subsystems are also of the size to rack up efficiently in a habitat module. The four-man-sized subsystem may not remain the target size for development, but, if it does change, it is likely to remain within a three- to six-man range. At some point in the development of advanced lunar bases when crew sizes reach above approximately 15 to 20 (an estimate), individual four-man-sized subsystems may no longer be efficient.

Advantages may be gained by upscaling the subsystems. A reasonable estimate of the time in the base development at which the optimum subsystem size will change is the point at which the base is supported by a "city utility" type system as opposed to individual ECLS systems for each habitat unit.

Resupply Interval

This factor is tightly coupled with crew size relative to its impact on launch and resupply logistics. Once the quantity of expendables per man-day has been determined, a simple

multiplication with crew size and resupply interval quickly establishes the resupply weight and volume logistics. The ECLS system expendables will probably not be the prime factor in establishing the resupply interval. The interval will most likely be determined by crew rotation needs, base assembly schedules, or possibly by the need to supply replacement units and maintenance items for the various lunar base systems, including the ECLS system.

Redundancy and Fail-Operational/Fail-Safe Ground Rules

A discussion of the rationale supporting redundancy and fail-operational/fail-safe ground rules is beyond the scope of this paper. There will be many disciplines involved in setting the ground rules, and the ECLS discipline is one of them. Certainly the reliability of the ECLS system and the time-related impact of subsystem failures within the ECLS system will be a key issue in setting the ground rules; however, this paper is addressing only the impact of the ground rules on launch and resupply logistics.

A very conservative and oversimplified ground rule would be that, because the ECLS system is so vital to a lunar base, the entire system has to be redundant. That would double the launch weight and volume and result in penalties that are not acceptable. There is no reason, for example, for including two sets of stored food, two galleys, and two sets of duct work for air distribution. The ECLS system engeineer would need to examine the total system on a subsystem-by-subsystem (probably component-by-component) basis relative to the ground rule. Then the impact of redundancy on logistics could be assessed. In the SAB study of ECLS systems for a lunar base, an assumption was made that only the air revitalization subsystem of the proposed ECLS system for a habitability module needed to be redundant. The assumption is valid only for that specific study. Adding the redundant air revitalization subsystem increased the launch weight by 872 lb and the launch volume by 69.1 ft^3. If a redundant water reclamation subsystem had been included, an additional 392 lb of launch weight and 38.5 ft^3 of launch volume would have been added. These values are for redundant reclamation units only. They do not include additional tankage and plumbing. Obviously redundancy adds significant increases in weight and volume. It also drives up the initial and total mission costs. Mission planners and project managers should work closely with the ECLS system engineer to develop a sensible rationale for redundancy so that mission safety and success can be achieved with minimum impact on the logistics.

Degree of Water Loop Closure

By examining the needs and effluents values on Fig. 1, one can initially conclude that the water loop can be closed. Water needs (water that must be supplied as free water) total 45.17 lb per man-day (1.58 + 4.09 + 4.00 + 8.00 + 27.50). Water that is available for recovery totals 46.83 lb (3.31 + 4.02 + 12.00 + 27.50). The additional water was gained from the water in the food and in water produced by metabolism. Then, if one assumes 100% recovery, the loop should show a net daily gain. Most engineers realize 100% recovery is not feasible, but 97% recovery has been suggested in numerous space station planning documents. At 97% recovery, the water balance still shows a slight net gain, 0.25 lb per man-day. Past experience with development testing, however, indicates that the 97% recovery is not realistic.

There are many ways in which useful reclaimed water can be lost. Two of the leading waste-water processing techniques end with a brine (residual water with a high concentration of salts and solids) that will likely be dumped, or stored and returned to Earth. There may be batches of reclaimed water that will not meet water quality standards, and reintroducing them into the recovery subsystem is not desirable. Leaks and spills will occur. The net result is that 90% recovery is more realistic, although, in fact, it still may be an optimistic estimate. Assuming 90% recovery to be achievable, the water balance now shows a net daily loss of 3.02 lb per man-day. This loss translates to 12.08 lb per man-day for a crew of four and 10-87 lb per crew for a 90-day resupply period. Based on shuttle tankage data, typical water tanks carry 162 lb (165 lb - 3 lb ullage) of available water and weigh 50 lb. Thus, approximately seven tanks with a total weight of 350 lb are needed. The total weight at the 90% recovery level is now 1437 lb per 90-day period. Any variation from the 90% recovery causes a proportional change in total weight. The primary message in the above discussion is that a closed water loop cannot be assumed, and the recovery percentage that is achieved will significantly impact launch and resupply logistics.

Volume of Pressurized Structures

Supplying the gases for pressurizing structures on a lunar base will always significantly impact launch and resupply logistics. In the SAB lunar base study previously mentioned, calculations determined that 554 lb of O_2 and tankage and 1573 lb of N_2 and tankage were required to pressurize and support the habitat area for the first 90 days. The pressurized volume was 9383 ft^3 (1 module and 2 nodes) at a pressure of 14.7 psia. A two-gas atmosphere was assumed, and an O_2 recovery subsystem was included. After the first 90-day period, each 90-day resupply must include 384 lb of O_2 and tankage and 742 lb of N_2 and tankage. Note that even though the ECLS system recovers metabolic O_2 from CO_2, O_2 make-up is required for emergency repressurization, leakage, and airlock losses. Transporting these gasses cannot be avoided, since the habitat area will always be pressurized and losses will always occur. The O_2 resupply may be eliminated, however, when the LOX production facility becomes operational. The key gas is the diluent, most likely N_2. It is 79% of the total by volume, and there appears to be no source for producing sufficient quantities of it on the Moon. The supply of N_2 will always be a high-cost logistics item.

Pressurizing structures other than those of the habitable area greatly expands the problem of gas logistics. The surface structures that have been proposed for storage and maintenance shed, LOX production plants, observatories, etc., are all large in volume. Most likely some of these structures do not need to be pressurized, but if they do, the supporting logistics costs will be high. Once the decision is made to pressurize a structure, the costs in terms of weight, volume, and the power extend well beyond just the costs of the gases and tankage. If a structure is to be pressurized, a pressure control subsystem has to be added. If crewmen enter and exit the pressurized structure, airlocks need to be added. If airlocks are added, pump back units have to be added, because a complete loss of gases in the airlock during each operation cannot be tolerated.

During the lunar base study previously mentioned, three structures other than the habitat area were proposed. They included a pilot LOX production plant with a volume of 4000 ft^3, an observatory with a volume of 4000 ft^3, and a storage and

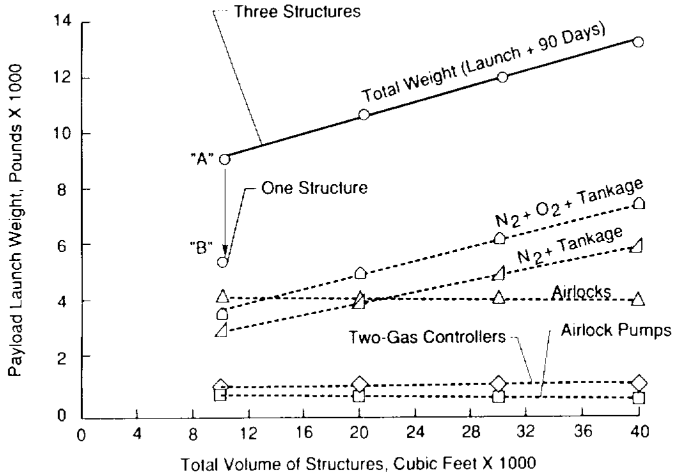


Fig. 2. Weights incurred to pressurize large facilities (structure volume is a total of three structures).

maintenance shed with a volume of 3500 ft^3. During the basic study, the entire 11,500 ft^3 was assumed to be unpressurized, but in order to scope the problem should the facilities need to be pressurized, the payload launch weight was calculated and plotted (Fig. 2). The structure volume given on the abscissa assumes the volume is a total of three structures. Thus, in addition to the gases, six airlocks (two per structure), three airlock pumps, and three two-gas controllers are needed. The resultant total weight for initial launch and the first 90 days of use can be extracted from the "total weight" plot. To pressurize the three structures totaling 11,500 ft^3 requires 9490 lb of gases and equipment in addition to the actual structure weight. The study assumed the use of cryogenic O_2 and N_2 transported from Earth. The equivalent weights for other structure volumes (combined volume of three structures) can be determined from the plot. Another interesting observation shown on the figure is the relationship between obtaining the volume in one structure (new design) that is equivalent to the combined volume of three space station modules. The 10,000 ft^3, three-structure total weight anchor point "A" is displaced downward to point "B." The total weight is reduced 41% from 9173 lb to 5425 lb. The large reduction is the result of elimination of four airlocks, two pumps, and two gas controllers.

These calculations were based on certain assumptions and a limited database, but the absolute values are not important at this time. The relative values do, however, support an important conclusion. The total system costs (weight, volume, and power) of pressurizing large structures will be high. Lunar base planners must continually be aware of the impact of adding large, pressurized structures. Remember that the majority of the pressuring gas will be N_2, some of it will be lost, and it is not likely that N_2 can be obtained in the quantity needed from a lunar resource.

AIRLOCK OPERATIONS

Airlock operations are tightly coupled to the subject of pressurized structures. The presence of a pressurized structure implies crew ingress and egress, and with each operation of an airlock, pressurization gases are lost. Examples from the SAB lunar base study illustrate the impact of airlock operations on logistics. The study assumed airlocks with a volume of 100 ft^3 supporting passage of one crewman. If the entire airlock volume, beginning at a pressure of 14.7 psia, were dumped with each airlock operation, 8.04 lb of pressurization gas would be lost. The operational scenario for the base resulted in 10 airlock operations per day (24 hr). With a 90-day resupply, 7236 lb of gases would be lost each resupply period. That magnitude of loss could not be tolerated, so a system (pumps, valves, and controller) was added to pump back 90% of the airlock gases with each operation. Thus, only 723.6 lb of gas were lost, but that remains a sizeable loss that must be replenished with each resupply. Of course, tankage weight has to be added to arrive at the true logistics cost. The 90% pump-back level was determined to be practical after trading off size relationships between airlock and module or node, pumping time, pump efficiency, and pump size and power requirements. To recover more than 90% requires an unreasonable pumping time or a much larger pump. A calculation was also made relative to a base in which the three operational facilities (LOX plant, observatory, and storage and maintenance shed) were pressurized and needed airlocks. The airlocks were chosen to support simultaneous passage of two crewmen. The airlock volume was 226 ft^3. Again, if 10% of the atmospheres were lost each time, 1635 lb of gas would be lost each 90 days. The airlock operations scenario, the airlock volume, and the amount of gas lost during each operation would combine to have a significant impact on the launch and resupply logistics.

ADDITIONAL FACTORS THAT MAY BECOME DRIVERS

Up to this point in the paper, the discussions have focused on mission ground rules, mission characteristics, and systems other than the ECLS system that are design drivers inherited by the ECLS system engineer. The implication is that given all the details of these, the ECLS system engineer will produce an optimum system for the lunar base. This assumption is overly optimistic. In order to assure that the technology of regenerative systems is ready when needed, more emphasis has to be placed on specific portions of the development cycle. Figure 3 can be used to illustrate the needed emphasis. The candidate technology readiness level column on the left side shows the sequence through which processes and related hardware components (a candidate subsystem) evolve from concept to operational flight hardware. The eight levels of technical readiness have been accepted by the ECLS system community as a proper scale for rating the readiness levels. The hardware sequence bar chart on the right of the figure was added by the authors to relate the type of hardware required to move the candidates through the readiness level.

One problem with the figure is that all the steps and substeps on the left and all the hardware-type bars on the right give a visual appearance of all being about equal in scope. That is entirely misleading. Advancing from level 1.0 through 3.0 using laboratory and breadboard models is easy. The time element is short, the costs are relatively low, and progress can quickly be shown by proving the "technical feasibility" of a process. At that point, however, the scope of the job changes. Levels 4.0 and 5.0, sometimes level 6.0 also, are much more lengthy, require many more resources in dollars and manpower, and are not scientifically or technically exciting. For these reasons they have been more difficult to sell to sponsoring agencies.

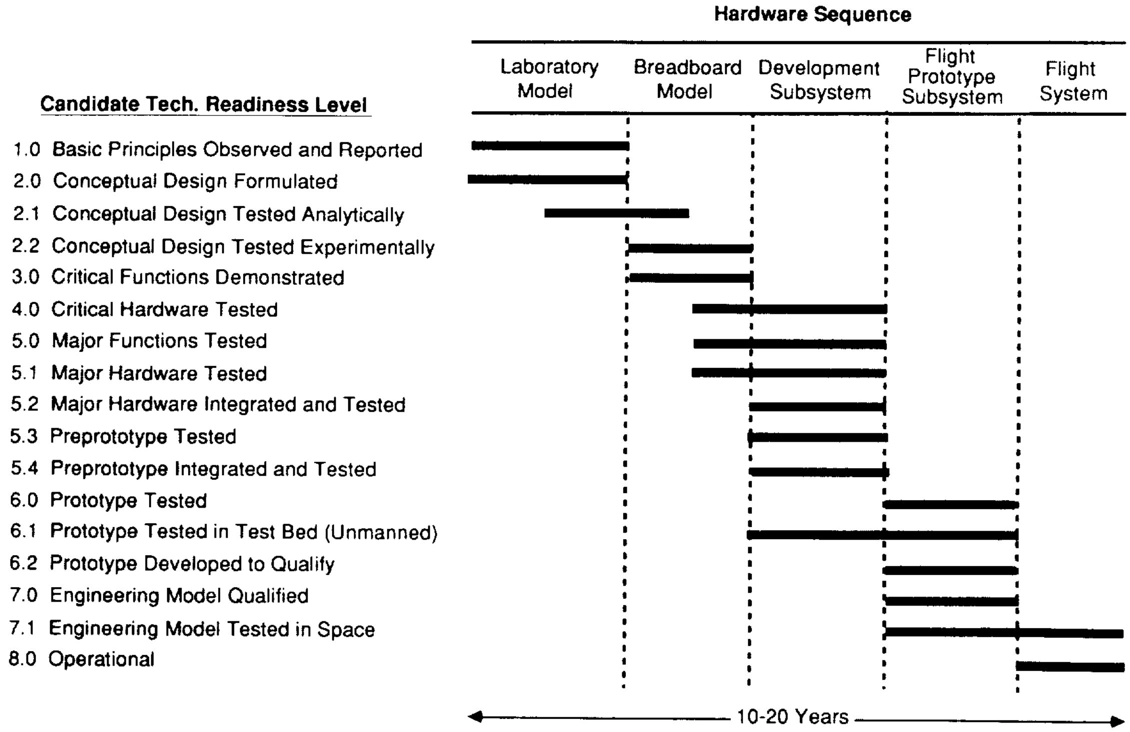


Fig. 3. The ECLS system technology development sequence.

The dichotomy present, however, is that it is steps (levels) 4.0 through 6.0 that advance the technology to a usable level. Real long-term use problems of materials selection, materials degradation, long-term component reliability, integration, maintenance of mass balance, process control (a pacing technology for integrated systems), microbiological control, automation, and fault detection and isolation are encountered and must be solved in order to reach levels 7.0 and 8.0. Noticeable efforts have been made in the past on these important steps by several NASA centers. The Langley Research Center made the early progress in integrated ECLS systems during the late 1960s and early 1970s. The Ames and Johnson Space Centers made significant progress in long-life testing of components and subsystems in the 1970s and early 1980s. The Marshall Space Flight Center is now engaged in an integrated ECLS system development and testing program focused on the early space station. These types of efforts must be expanded and given more emphasis because the job is more difficult than it may appear. It is also apparent on the "bottom line" that a typical 10-20 yr development period experienced in the past cannot be tolerated. Fortunately ECLS system engineers are not faced with beginning at level 1.0. Many of the proposed techniques are now in levels 4.0 and 5.0. They must be pursued vigorously, however, or else the lack of technology readiness may be the most overpowering design driver of all.

CONCLUDING REMARKS

Early mission planning must include parallel consideration of all technical disciplines that contribute to the total lunar base infrastructure. Ground rules derived unilaterally by mission planners may impose unnecessary penalties on the ECLS system design. Conversely, system designs developed unilaterally by the ECLS system engineer may limit the operational flexibility of the base or may violate some ground rule considered important by the scientific community.

There is no single ECLS system that is most applicable to a mission of "x" days with a crew of "y." All the mission parameters and details of the other systems must be factored into the ECLS system design.

Mission planners and systems engineers, including the ECLS system engineer, should refrain from using the term "closed loops." Even with the best regenerative processes, some expendable material that must be resupplied is included. The resupply logistics required to support the lunar base ECLS system, even if regenerative, is significant.

Perhaps the most important ECLS system design driver of all those discussed is the technology status of candidate processes and subsystems. The development cycle of regenerative ECLS system techologies is lengthy, laborious, and expensive. It will require great diligence on the part of the ECLS system engineers and their sponsors to assure that when the time arrives to design a lunar base, it is the mission parameters that drive the ECLS system design rather than the lack of an adequate technology baseline.

REFERENCES

Hall J. B., Ferebee M. J., and Sage K. H. (1985) Environmental control and life support systems technology options for space station application. In *Papers Presented to the Fifteenth Intersociety Conference on Environmental Systems*. SAE, San Franciso.

MacElroy R. D. and Klein H. P. (1985) The evolution of CELSS for lunar bases. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 623-633. Lunar and Planetary Institute, Houston.

Quattrone P. D. (1981) Extended mission life support systems. In *Papers Presented at the Case for Mars Conference*, Boulder Center for Science and Policy, Boulder.

Sedej M. M. (1985) Implementing supercritical water oxidation technology in a lunar base environmental control life support system. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 653-661. Lunar and Planetary Institute, Houston.

LIFE SYSTEMS FOR A LUNAR BASE

Mark Nelson

Institute of Ecotechnics
24 Old Gloucester Street
London WCI England

Philip B. Hawes

Sarbid Ltd.
P.O. Box 689
Oracle AZ 85623

Margret Augustine

Space Biospheres Ventures
P.O. Box 689
Oracle AZ 85623

Biosphere II is designed to be a materially closed and informationally and energetically open system capable of supporting a human crew of eight. Currently under construction by Space Biospheres Ventures near Oracle, Arizona, Biosphere II is scheduled for full closure and an initial two-year operation with a crew of eight beginning in the fall of 1990.

INTRODUCTION

The Biosphere II project is pioneering work on life systems that can serve as a prototype for long-term habitation on the Moon. This project will also facilitate the understanding of the smaller systems that will be needed for initial lunar base life-support functions. In its recommendation for a policy for the next 50 years in space, the National Commission on Space urged, "To explore and settle the inner Solar System, we must develop biospheres of smaller size, and learn how to build and maintain them" (*National Commission on Space*, 1986). The Biosphere II project, along with its Biospheric Research and Development Center, is undertaking work to meet this need. In this paper we will give an overview of the Space Biospheres Ventures' endeavor and its lunar applications.

BIOSPHERE II: OVERVIEW AND SCALE

The total airtight footprint of Biosphere II is about 137,416 sq ft or 3.15 acres, with a volume of 7.2×10^6 cu ft (see Table 1). Of this area, the main structures of the Biosphere II, which house rainforest, savannah, desert, marsh, ocean, intensive agriculture, and human habitat areas, are 98,000 sq ft with a volume of 5.4×10^6 cu ft. On its longest side, it measures approximately 550 ft from the rainforest to the desert area.

Two variable volume chambers, or lungs, will be sealed from the outside atmosphere and be continuous with the atmosphere of Biosphere II. These lungs cover 39,200 sq ft, with a volume of about 1.7×10 cu ft. Because air expands and contracts with changes of temperature, these increases or decreases in its internal air-volume pressure would cause the glass or seals to break due to differential pressure if such an expandable chamber were not provided.

Biosphere II will be primarily solar powered—in terms of solar radiation for photosynthesis. Electrical generation is primarily by natural gas, with diesel generators for back-up. Waste heat from the generators will be used to chill or heat water used for temperature control, thus reducing resource needs by about 20%.

TABLE 1. Dimensions of Biosphere II.

Area Footprints	Feet	Meters	Acres	Hectares
Intensive Agriculture	24,020	2,232	0.55	0.22
Habitat	11,592	1,077	0.27	0.11
Rainforest	20,449	1,900	0.47	0.19
Savannah/Ocean	27,500	2,555	0.63	0.26
Desert	14,641	1,360	0.34	0.14
West Lung (Airtight Portion)	19,607	1,822	0.45	0.18
South Lung (Airtight Portion)	19,607	1,822	0.45	0.18
Total Airtight Footprint	137,416	12,766	3.15	1.28

Volumes	Cubic Feet	Cubic Meters
Intensive Agriculture	1,336,012	37,832
Habitat	377,055	10,677
Rainforest	1,225,053	34,690
Savannah/Ocean	1,718,672	48,668
Desert	778,399	22,042
Lungs (At Maximum)	1,770,546	50,137
Total	7,205,737	204,045
Soil, Water, Structure, Biomass	671,635	19,019
Air	6,534,102	185,026

The hydrosphere of Biosphere II will contain approximately 1.3×10^6 gal of water, 1.1×10^6 in the ocean area and about 200,000 gal of freshwater. In Biosphere II the surface proportion of ocean to land will be 15:85. The productivity of Biosphere II's marine systems is expected to be high because coral reef and marsh ecosystems are included.

Logistical constraints, e.g., the collection or acquisition of full-sized plant specimens, dictate that the plant biomass at the commencement of closed-system operations will be considerably less than those anticipated at equilibrium. To accommodate the transformation of this immature, or growing, system requires the provision of reservoirs of material for uptake and conversion to organic tissue during this equilibration of the system.

The anticipated equilibrium biomass of Biosphere II is 70 tons. With a relatively small mass of atmosphere, hydrosphere, and geosphere to act as buffers, the biogeochemical cycles will operate rapidly (see Table 2). For example, CO_2 will cycle daily compared to an estimated cycle in our global biosphere of 10 to 12 years. The persistence of biospheric systems will be measured in numbers of the various cycles it sustains, as well as in calendar years. The percent availability of elements in the biotic cycle and their distribution in component parts will be important measurements, as this has been a major concern in previous closed ecological systems (*Hanson,* 1982; *Starikovich,* 1975; *Fong et al.,* 1982).

TABLE 2. Atmospheric system of Biosphere II.

	Pressure			Total Mass
	MM-HG	PSI	KPA	Kilograms
Oxygen	136.1	2.63	18.13	31,800
Nitrogen	507.6	9.82	67.67	103,775
Carbon Dioxide	0.21	0.004	0.028	67
Water Vapor	13.4	0.26	1.79	1,761
Argon	6.1	0.12	0.83	1,782

Pressures do not total standard 760 mm Hg or 14.7 psi because at 3900′ elevation at project site, atmospheric pressure is about 663 mm Hg (18.8 psi).

BIOSPHERIC DESIGN: INTERPLAY OF BIOMES

In designing man-made biospheres for stability, diversity, and persistence, biomes have been used as the key structural elements. The term "biome" is here used in a sense analogous to its usual definition in global ecology: "the biota are organized into geographically distributed classes called biomes, which are types of ecosystems" (*National Research Council,* 1986); or systems ecology: "Regional climates interact with regional biota and substrate to form layers, easily recognizable community units ... in a given biome the life forms of the climatic climax vegetation is uniform" (*Odum,* 1971). The biomes, or major ecosystem areas, of Biosphere II will be controlled to different temperature and humidity regimes, and be dominated by characteristic vegetation and soil types as are the natural biomes of the Earth. The biomic areas of Biosphere II interact in its gas and mineral cycles.

In Biosphere II there are seven biomes, five modeled on wilderness biomes (rainforest, savannah, desert, marsh, and ocean) and two modeled on the major anthropogenic types of land use (intensive agriculture and human habitat) (Figs. 1 and 2). All the biomes are tropical. With the project's location in southern Arizona with its mild winters, hot summers, and great year-round sunshine, to do otherwise would have incurred a great price in energy required for cooling. The selection for various analog Earth biomes for the areas in Biosphere II has been coupled with the inclusion of species that can play a role in providing food, fiber, pharmaceuticals, and aesthetics, as well as functioning in the maintenance of atmosphere and completion of natural cycling processes. Indicator species are also included to assist in monitoring key variables such as pH, temperatures, and trace gas contaminants.

The tropical rainforest structure is approximately 90 ft tall. From the "cloud forest" ecosystem a stream flows down a waterfall, across the forest floor, and into the adjoining savannah. Dr. Ghillean Prance, now director of Kew Gardens, and the Institute of Economic Botany, New York Botanic Garden, were the rainforest design consultants. The Amazon rainforest was used as the analog for Biosphere II. Design of such a small area to provide the function and long-term genetic viability of a rainforest parallels important questions of research in the planet's rainforests (*Myers,* 1979).

The stream then flows through the savannah biome located at the top of rock cliffs. The savannah biome will include several habitat areas: a gallery forest, grassland, and a periodically flooded ecosystem. Dr. Peter Warshall of the Office of Arid Land Studies, University of Arizona, designed the savannah using plant species from Africa, Australia, and South America. The savannah will house about 150 species and 5000 organisms at closure, not including termites and other arthropods. The thorn scrub forest marks the ecotone or transition area between the savannah and the desert biome.

Next, the stream enters the marsh biome, which includes a freshwater area that grades up in salinity to a saltwater marsh. This estuarine marsh is modeled after the Florida Everglades. The oceanic system is 25 ft at its deepest point and includes a coral reef ecosystem and lagoon at one end. Wave action, required for the ecological maintainance of the coral reef, will be supplied mechanically through vacuum pumps. Dr. Walter Adey of the Marine Systems Laboratory, Smithsonian Institution, is design consultant for the marsh and ocean systems.

The desert biome is patterned after a coastal fog desert, such as the Vizcaino Desert in Baja California, and is populated with species adapted to low rainfall but high humidity. Dr. Tony Burgess of the Eco-Hydrology Project, USGS, Tucson, desert biome consultant, has designed five major habitat regions in this biome that will provide econiches for about 100 species, and a population that will vary between 50,000 individuals in the flowering season of the desert annuals to 900 individuals during the desert's inactive season.

The atmosphere is one continuous system throughout Biosphere II. Air circulation will be accomplished by convection and by technical means. Differences in elevation, temperature, and in some cases structural, diversions of air-flow have been built into the design. Air circulation is an important factor in pollination for those plants that utilize wind pollination, and air circulation sometimes affects the extreme temperatures some species can tolerate. Air handling units in all the biomes will ensure the circulation of air and coupled with heat-exchange water systems can provide cooling or heating as required.

The white steel-clad space frame domed building, the human habitat, is analogous to an urban center, and will include apartments, laboratories, computer and communications facilities, workshops, libraries, recreation, and similar facilities for the eight resident researchers. The human habitat is designed to be fully informationally linked to the outside via computer teleconferencing, television, video, radio, and telephone. A mission control building overlooking the project will receive data coming from the more than 2000 sensors inside Biosphere II. In addition,

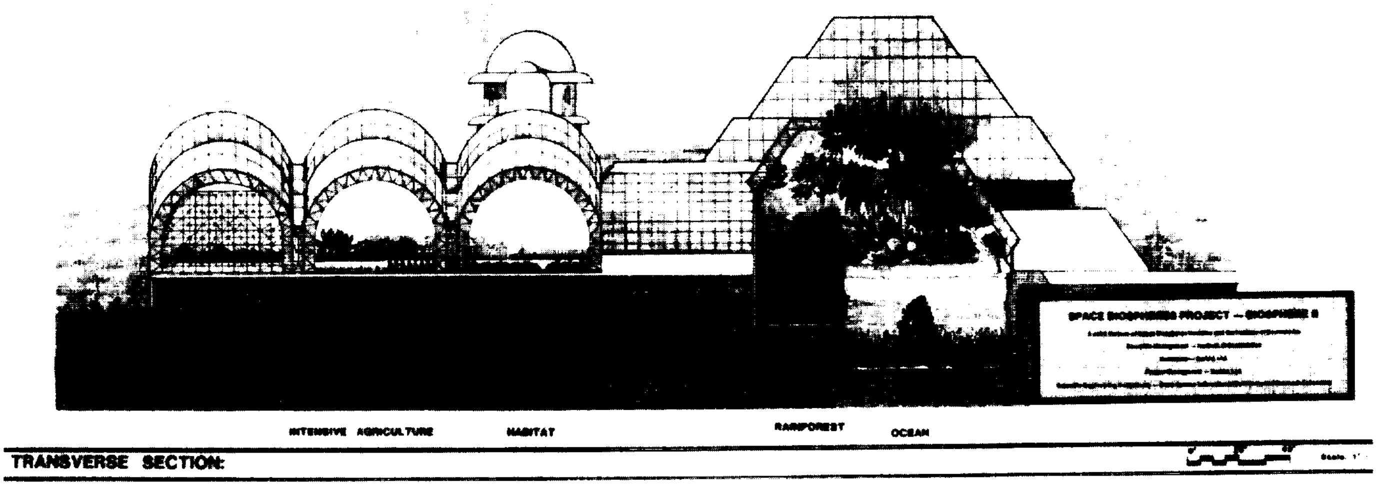


Fig. 1. Design drawing of Biosphere II showing intensive agriculture area (with rounded barrel vault roof), habitat, rainforest, and ocean.

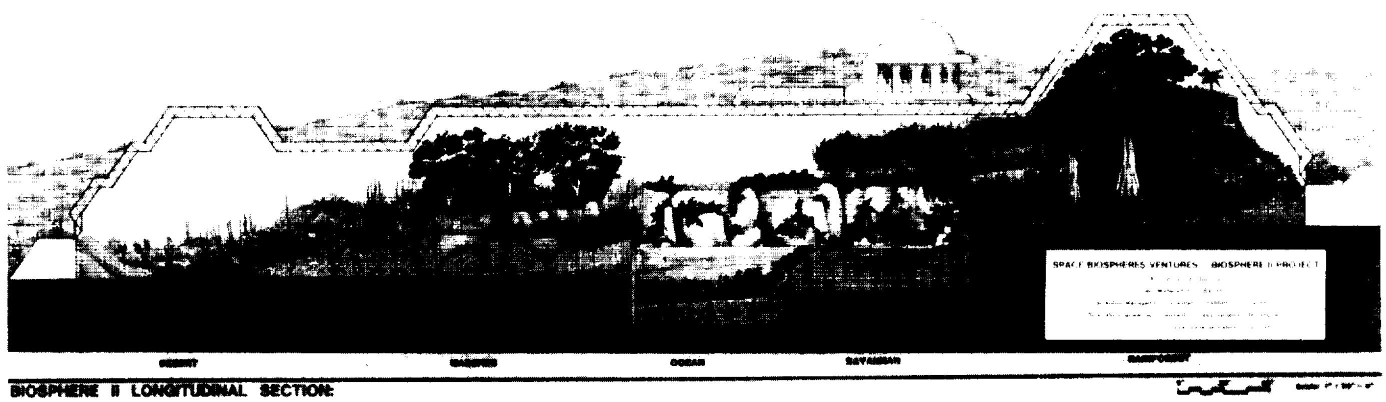


Fig. 2. Cross-sectional view of Biosphere II rainforest, savannah, desert, marsh, and ocean areas. Dome of habitat protrudes to the west of these "wilderness biomes."

cooperating research centers can be networked, beginning with those currently working on the project, permitting data assessment for evaluation and management of this project, and for comparative studies of global functioning.

Adjacent to the human habitat is the intensive agriculture area. Some 50 species and 150 cultivars will be grown, with about 30 in cultivation at a time. Near the broad terraces of plant crops are animal areas for chickens, pygmy African goats, and Vietnamese pot-bellied pygmy pigs. The aquaculture system contains tilapia fish and biofilters where naturally occurring microbes convert the ammonia of fish waste into nitrates. The aquaculture water is coupled with rice production bays and supports algae and the waterfern Azolla, for fish and animal feed. The Environmental Research Laboratory of the University of Arizona, directed by Carl Hodges, serves as design consultant for the intensive agriculture as well as working on aspects of the project's scientific engineering. Since Biosphere II is materially closed, the intensive agriculture area will produce all of the food required for eight people, year round (*Hodges*, 1987).

Together, the intensive agriculture and human habitat systems could serve as a prototype for short-term space life-support systems such as on a microgravity space station or for early stages of the lunar base.

Besides domestic animals, Biosphere II will be habitat for various birds, reptiles, amphibians, small mammals, insects, and other invertebrates. Biomic design work has included mapping food webs, including provision of alternative pathways and redundancy, and study of individual behavior patterns to provide sufficient food and habitat to support the animal species without endangering other populations. This evaluation will also ensure that ecological functions such as nutrient recycling and pollination are fulfilled.

Collections are underway for the plant, fungus, and insect and other arthropod species selected for inclusion in Biosphere II at closure in 1990. Collections have or will be made in Guiana, Colombia, Baja California, the Everglades, Australia, Africa, and Puerto Rico. A diverse collection of mature rainforest species has also been donated from the Missouri Botanical Garden Climatron. Plants are transplanted or propagated from seed, cuttings or tissue culture, and cultivated in greenhouses to acclimate and reach the desired state of maturity before being transplanted to Biosphere II. An insectary is presently under construction to house and propagate many of the 250 insect species currently planned for the project. The Bishop Museum Department of Entomology, under direction of department chairman Dr. Scott Miller, has been contracted for selection of species, and design of maintenance and monitoring.

BIOSPHERIC RESEARCH AND DEVELOPMENT CENTER

In preparation for the construction of Biosphere II and to facilitate applications of ecological life-support systems for space environments, Space Biospheres Ventures (SBV) has set up the Biospheric Research and Development Center. In full operation at present, this research and development complex includes the SBV Plant Tissue Culture Laboratory, Analytical Laboratory, 17,000-sq-ft. Experimental Intensive Agriculture greenhouse for horticulture, animal husbandry, and aquaculture, the 17,000-cu-ft Biosphere Test Module, and four quarantine and accession greenhouses for the collection and propagation of plants destined for Biosphere II. This complex also serves as a training facility for "Biospherians," prospective candidates for the crew of Biosphere II.

In the Experimental Intensive Agriculture greenhouses, research on cultivar selection and production, nutrient recycling, waste treatment, composting, and harvesting methods is being conducted (Fig. 3). Several cultivation methods have been tested, including soil- and compost-based systems, as well as hydroponics and aeroponics. Biosphere II will use a soil medium for plant cultivation and air purification by pumping air through the cropping areas.

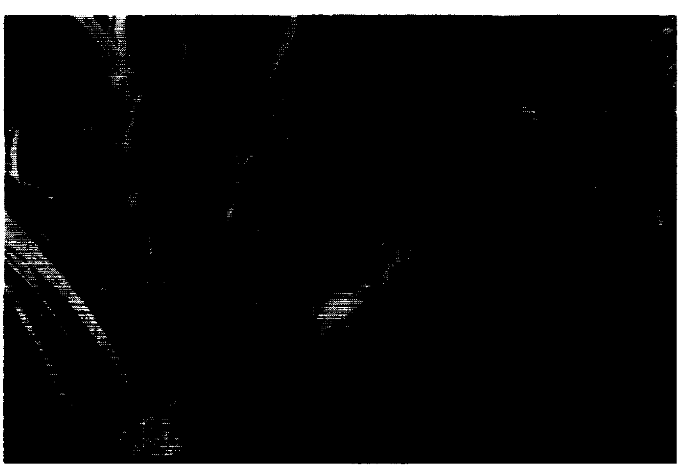


Fig. 3. View of some of the crops in the prototype intensive agriculture research area at the Biospheric Research and Design Complex at Space Biospheres Ventures.

The aquaculture system is designed to produce two meals of fish per person per week. The water from the aquaculture is applied to crops. After being filtered through the soil, the water is returned to the fish tanks. The fish eat water ferns, algae, roots of aquatic plants, and food grown in the greenhouses.

A primary function of the agriculture system is to establish a diverse soil community that will include rich microbial assemblages and invertebrate fauna, functioning to maintain the cycling of nutrients through the system. These biological systems will also be important to the purification of the atmosphere from potential toxic buildups through their use as soil bed reactors through which the entire air volume of Biosphere II can be pumped.

Screening of potential crop plants from around the world is currently underway. Production of edible and total biomass, ease of harvest and processing, toleration of environmental variance and ability to intercrop are being assessed. Some of the crops currently being grown in the Experimental Intensive Agriculture are rice, sorghum, alfalfa, soybeans, cowpea, wheat, potato, tomato, papaya, banana, and sweet potato. Small patches of each crop are used, thus rotating the harvest schedule in order to minimize the perturbation of the system at any given time.

No chemical pesticides have been used in the agricultural greenhouses and they will not be employed in the Biosphere II agricultural system. Rather, an integrated pest management system has been developed for the exclusion, resistance to, and avoidance of pests and pathogens. Biological, mechanical, and cultural controls are all employed.

SBV PLANT LABORATORY

The SBV Plant Laboratory conducts plant tissue culture work for Biosphere II, for propagation of endangered species, and for commercial agriculture and nurseries. Tissue culture allows the rapid propagation of plants from a very small piece of meristem tissue material, and enhances the ability to select for desired characteristics, such as resistance to pests or disease. This technique can provide a large genetic reservoir for Biosphere II and other closed systems in a relatively small area.

The Plant Tissue Culture Laboratory at SBV is currently concentrating on two orders of the plant kingdom: the Lilliales, and the Zingiberales. The techniques developed in micropropagation of a diversity of life forms can be used in the export of plants from Earth to minimize weight and volume requirements for the innocula of space and lunar life systems.

BIOSPHERE II TEST MODULE

The Biosphere II Test Module, approximately 27×27 ft in area and 17,000 cu ft in volume (including its lung), was constructed to test constructioon and sealing techniques, cooling and computer monitoring, and data acquisition systems. The chamber construction is spaceframe and glass, with a stainless steel liner to seal the system from the underlying soil (Fig. 4).

The Test Module is now being used for closed ecosystem experiments with plants, soils, and insect populations to test generation and maintenance of atmospheric gases, plant growth, photosynthetic efficiency in closed systems, and overall system dynamics. Observation of pollination and behavior of potential pests and pathogenic factors in closed ecological systems has also been conducted in the test module. The facility is the largest materially closed system in operation in the world.

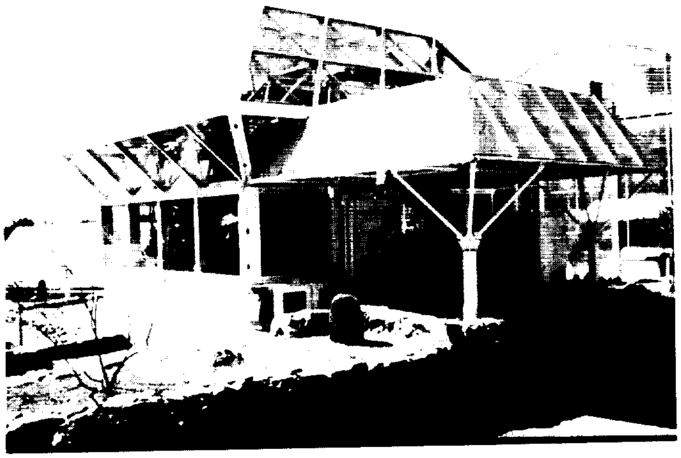


Fig. 4. The Biosphere II Test Module, which is 12,800 cu ft of volume in the biochamber. When the variable volume chamber is included, the total is about 17,000 cu ft. Experiments have been conducted in it since January 1987, and are ongoing, including human closed ecosystem work.

In operation since January 1987, current experiments include studies of plants representative of the planned ecosystems of Biosphere II, soils and soil fauna, and insect populations sealed for up to three-month periods. During these experimental closures, internal computer sensors continuously monitor O and CO_2 and regularly sample other atmospheric gases for evaluation via gas chromatography. Trace gases are being measured in parts per billion.

There are continuing studies on the biomass of primary producers and consumers, pollen dispersal, and pollination success under conditions of high humidity and low air circulation, and microbial function analysis and optimization of light availability.

Another series of experiments is exploring the maintenance of air quality through the use of microbial and biological systems. Research has demonstrated effective removal of ethylene, methyl mercaptan, methane, carbon monoxide, and other trace gases (J. Allen and coworkers, unpublished data, 1988; *American Conference of Industrial Hygienists,* 1987).

Human experiments in the Test Module have included a three-day closure in September 1988, both preceded and followed by a period of closure without the person inside, a five-day closure in March 1989, and a 21-day human closure in November 1989 (Fig. 5). These were the first closed ecological systems experiments to include complete waste recycling as well as food production and air and water regeneration using bioregenerative methods.

HISTORY OF BIOSPHERIC SYSTEMS

Biospherics, or the science of biospheres, is a young discipline. The term biosphere was first used by Eduard Suess in 1875 (*Hutchinson,* 1970), and the scientific concept developed by Vladimir Vernadsky since the mid 1920s (*Vernadsky,* 1986). The first laboratory-sized closed ecologial microbial systems date from 1967 in the work of Clair Folsome at the University of Hawaii, Basset Maguire at the University of Texas, Frieda Taub at the University of Washington, and Joe Hanson at the Jet Propulsion Laboratory (*Folsome and Hanson,* 1986; *Maguire,* 1978; *Taub,* 1974). At the Second International Workshop on Closed Ecological Systems held at Krasnoyarsk and Shushenskoye, Siberia, in September 1989, which was attended by scientists representing research in the field from the U.S., Europe, and the U.S.S.R., it was resolved that the term "biospherics" be used for the study of essentially materially closed ecological systems, which include planetary biospheres (the Earth's), man-made biospheric systems, fully or partly closed CELSS facilities, and laboratory ecospheres.

The most advanced work in the field before Biosphere II was conducted by Josef Gitelson and his team at the Bios-3 facility, Institute of Biophysics, Krasnoyarsk, Siberia. There, crews of two and three people operated a system some 300 cu m in volume for periods up to six months, recycling 100% of the air, 95% of the water, and producing about 50% of their food. This was the first time that men and higher plants were linked in an ecological system closed to this extent. Because of the low diversity of their system, organic trace gases had to be oxidized in a catalytic burner and the plants experienced problems. The solid waste materials of the people were not included in the cycling (*Gitelson et al.,* 1973).

Much has also been learned from Controlled Ecological Life Support Systems (CELSS) research underway in the U.S., U.S.S.R., and Japan. Ongoing research, such as the Kennedy Space Center Breadboard project will provide data in a field of extreme importance for the development of long-term bases on the Moon and elsewhere (*Averner et al.,* 1987).

Recent experiments in the Biosphere II Test Module, including the human and closed ecosystem experiments, have successfully tested the ability of such systems to perform complete recycling, and have confirmed computer modeling and predictions of systems dynamics based on earlier experiments.

LUNAR BASE MODULES

Space Biospheres Ventures is designing lifesystem configurations for microgravity and surplanetary bases. For permanent habitation, including the psychological health of the people, these systems are designed on a biospheric basis. This will ensure ecological stability and evolutionary potential, as well as offering its human inhabitants what Earth's biosphere provides: a place of relaxation and beauty. "Humans have evolved in the context of a biosphere—surrounded by the beauty, the diversity, the vitality and the mysteries of nature. Our future in space will depend both

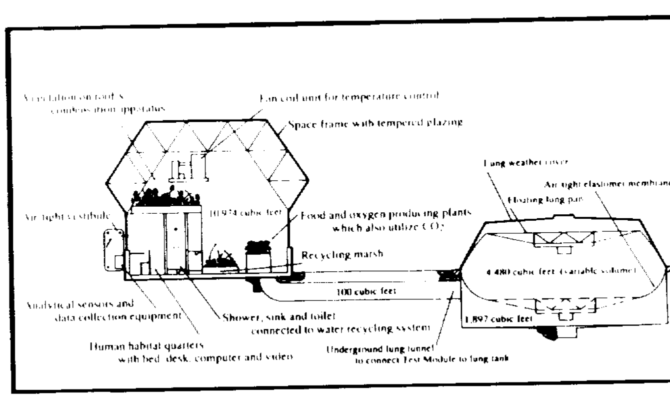


Fig. 5. Configuration of Biosphere II Test Module for Human and Closed Ecosystem experiments in September 1988, March and November 1989.

physically and psychologically on habitats that provide not only air, water and food, but also a stimulus to wonder and to learn, to participate in the sphere of life of which we are a part" (*Augustine,* 1987).

Initial steps in the creation of ecological life support capabilities for a lunar base will involve minimalist systems of the same order of magnitude as the Biosphere II test module. One scenario would see the use of the lunar landing vehicles as providing a nucleus area for the starting life support system. Subsequent landings could bring additional plants and genetic materials as well as processing tools and equipment for the utilization of lunar mineral resources, transformation of lunar regolith into soil, and liberation of useful elements such as oxygen.

These early and even temporary life support systems might not be totally materially closed. Purification and recycling of air and water and at least partial production of food requirements would be high priority tasks.

Current Soviet research on plants in lunar light cycles indicates that utilization of the natural 14-day light and dark cycle is feasible for adequate plant yields of tested crops (*Lisovsky,* 1987); however, utilization of artificial lighting will optimize use of plant-protected growing areas.

Such a lunar base will be designed as modular components, to be expanded progressively over time. The complete complex would include four units radiating outward and connected to a central "commons" area. Each of the four units would support six to ten people and could be oriented to provide various functions for the operation of the overall lunar base and its eventual expansion into additional biospheric units. These functional orientations would include transport, biological systems, mining, and processing operations. Each lunar complex might cover 12.5 acres, be 40×10^6 cu ft in volume, with an average height of 85 ft (*Allen and Nelson,* 1989).

All the biospheric units would be stocked with atmospheric gases derived as much as possible from the surrounding environment. Once operation of these lunar biospheric systems commences, further cycling of elements will be accomplished by microbe/fungus/plant/animal metabolism just as in the Earth's biosphere.

SUMMARY

Space Biospheres Ventures is developing project laboratories through its Research and Development Center and Biosphere II for the study and application of closed ecological systems. This research can play an important role in designing life support systems for initial and later configurations of lunar bases.

REFERENCES

Allen J. and Nelson M. (1989) *Space Biospheres,* 2nd edition. Synergetic Press, London/Tucson. 88 pp.

American Conference of Governmental Industrial Hygienists (1987) *Threshold limit values and biological exposure indices for 1987-1988.*

Augustine M. (1987) Biosphere II: The Closed Ecology Project. AAS-86-119. In *The Human Quest in Space,* Vol. 65, Science and Technology Series (G. L. Burdett and G. A. Soffen, eds.), pp. 243-254. American Astronautical Society, San Diego.

Dempster W. F. (1989) *Biosphere II: Technical Overview of a Manned Closed Ecological System.* SAE, Intersociety Conference on Environmental Systems, San Diego. 5 pp.

Folsome C. E. and Hanson J. A. (1986) The emergence of materially closed system ecology. In *Ecosystem Theory and Application* (N. Poulinin, ed.), pp. 269-288. Wiley, New York.

Fong F. and Funkhouse E. A. (1982) Air pollution by algal cell cultures. *NASA-CR-166384.* 33 pp.

Gitelson I. I. et al. (1973) *Life Support System with Internal Control Based on Photosynthesis of High and Unicellular Plants.* L. V. Kinrensky Institute of Physics, SD Academy of Sciences, USSR. 341 pp.

Hanson J. (1982) *Workshop on Closed System Ecology Summary Report.* Jet Propulsion Laboratory Publication 82-64. 41 pp.

Hodges C. (1987) The Closed Ecology Project: Agricultural and Life Sciences Background. In *The Human Quest in Space,* Vol. 65, Science and Technology Series (G. L. Burdett and G. A. Soffen, eds.), pp. 255-271. American Astronautical Society, San Diego.

Hutchinson G. E. (1970) The biosphere. In *The Biosphere* (Scientific American, ed.), p. 134. Freeman, San Francisco.

Lisovksy G. (1987) *International Workshop on the History, Current Projects and Future of Closed Ecological Systems.* Royal Society, London.

Maguire B. Jr. (1978) Some patterns in post-closure ecosystem dynamics (failure). In *Microcosms in Ecological Research* (J. P. Giesy Jr., ed.), pp. 319-332. U.S. Dept of Energy, Publ. Conf. 781101.

McElroy R. D., Klein H., and Averner M. M. (1985) The Evolution of CELSS for Lunar Bases. In *Lunar Bases and Space Activities of the 21st Century,* (W. W. Mendell, ed.), pp. 623-634. Lunar and Planetary Institute, Houston.

Myers N. (1979) *The Sinking Ark.* Pergamon, Oxford. 309 pp.

National Commission on Space (1986) *Pioneering the Space Frontier.* Bantam, New York. 211 pp.

National Research Council (1986) *Remote Sensing of the Biosphere.* Committee on Planetary Biology, Space Science Board, National Research Council. National Academy Press, Washington, DC. 135 pp.

Nelson M. and Allen J. (1989) Ecology and Space. *Jpn. Space Biol. J., 3,* 38-44.

Odum E. P. (1971) *Fundamentals of Ecology,* 3rd edition. Saunders College Publishing, Philadelphia.

Starikovich S. (1975) A month alone with Chorella. *NASA TT-F-16463.* 8 pp.

Taub F. (1974) Closed ecological systems. *Annu. Rev. Ecol. Syst., 5,* 139-163.

Vernadsky V. I. (1986) *The Biosphere.* Synergetic Press, London/Tucson. 82 pp.

LUNAR BASE CELSS— A BIOREGENERATIVE APPROACH

N93-13998

G. W. Easterwood[1], J. J. Street[2], J. B. Sartain[3], D. H. Hubbell[2], and H. A. Robitaille[1]

During the twenty-first century, human habitation of a self-sustaining lunar base could become a reality. To achieve this goal, the occupants will have to have food, water, and an adequate atmosphere within a carefully designed environment. Advanced technology will be employed to support terrestrial life-sustaining processes on the Moon. One approach to a life support system based on food production, waste management and utilization, and product synthesis is outlined. Inputs include an atmosphere, water, plants, biodegradable substrates, and manufactured materials such as fiberglass containment vessels from lunar resources. Outputs include purification of air and water, food, and hydrogen (H_2) generated from methane (CH_4). Important criteria are to (1) minimize resupply from Earth and (2) recycle as efficiently as possible.

INTRODUCTION

On the Earth, we exist within a dynamic life support system. Our atmosphere is maintained at static concentrations of certain gases by exchange with living organisms and physiochemical processes. Our water is continually being purified by evapotranspiration and by nature's filtering system, the soil. Nutrients, essential ions and compounds necessary for life, are immobilized by living organisms. Geochemical mineralization and decomposition of natural or synthetic biodegradable organic substrates are sources of nutrient availability. When nutrient deficiencies exist, chemical fertilizers, inorganic or organic, are applied by man to optimize biological and chemical relationships within the ecosystem.

Human habitation of the Moon will require environmental conditions similar to those on Earth where man evolved. Before bioregenerative closure within a lunar base, a synthetic atmosphere appropriate for human respiration must be prepared. Water, in quantities adequate for system function, must be synthesized. Higher plants must be included within the system for recycling purposes. Hardware, such as fiberglass containment vessels, can be manufactured from lunar regolith.

After preliminary development, implementation of a bioregenerative system composed of interdependent components of food production, waste management and utilization, and product synthesis will aid in the generation of a lunar ecosystem capable of supporting human life. Food will be produced from higher plants. Solid, liquid, and gaseous wastes must be managed to prevent disease or toxic compound release into the environment. These wastes will also be recycled since they contain vital components within a bioregenerative system. From waste recycling, essential products can be generated. Total system closure will only occur within a well-established lunar base after preliminary construction and development phases. Assuming an established lunar base, we will herein discuss some crucial aspects of a bioregenerative system. The oxygen cycle will not be discussed since regenerative oxygen extraction methods from ilmenite or magma electrolysis have been developed, and oxygen should not be limiting.

FOOD PRODUCTION— "FARMING" LUNAR SOIL

During the primary stages of lunar base construction and development, which might include 8 to 10 occupants, hydroponic systems may be used to grow plants for both food and partial gas exchange. Research is currently being conducted at the Kennedy Space Center (KSC) to develop and study hydroponic plant production systems for space habitats. Automated hydroponic systems would most efficiently utilize both area and mission specialists' time. However, as the size and number of occupants increases by an order(s) of magnitude during developmental phases (*Duke et al.*, 1985; *Burden and Angelo*, 1985) and total bioregenerative enclosure is required, lunar soil may be utilized for growing plants and as a deposition site for anaerobically digested residues. Although somewhat different from terrestrial rock and soil in composition and mode of formation, lunar soil possesses the precursor primary minerals of terrestrial soils. Major lunar minerals are olivine, pyroxene, and plagioclase feldspars (*Williams and Jadwick*, 1980). Since chemical weathering has not occurred on the Moon, mineral transformations to secondary products with greater stability have not occurred. Physical weathering induced by meteorite impacts has altered the mineralogy by forming glass and agglutinate (minerals in glass matrix) fractions. Olivines, pyroxenes, and volcanic glasses are some of the most soluble minerals in a chemical weathering environment on the Earth. Although relatively insoluble in water, their solubility is enhanced in the acidic environment produced during cropping.

Sources of acidity associated with the soil-plant system to promote mineral dissolution include (1) humification of residues, (2) plant root exudation, (3) acid-forming fertilizers, (4) hydration of Al, Fe, and to a lesser extent Mn ions, and (5) carbonate equilibria. Approximately 10% by weight of Apollo sample 12070

[1]The Land, EPCOT Center, Walt Disney World Co., P.O. Box 10,000, Lake Buena Vista, FL 32830-1000

[2]University of Florida, Soil Science Department, 2169 McCarty Hall, Gainesville, FL 32611

[3]University of Florida, Soil Science Department, 106 Newell Hall, Gainesville, FL 32611

was dissolved in weak acid (0.6-g sample in 350 ml 0.01 *M* salicylic acid) while 0.25% was dissolved in water during an 81-day incubation study (*Keller and Huang,* 1971). Ions essential for plants that dissolved from lunar soil include Mg, Fe, Ca, and low concentrations (approximately 10 μmol l^{-1} in acidic media) of K. In another study to determine the influence of lunar soil on higher plants, chlorophyll concentration was increased by 21-35% in tobacco callus as a result of enhanced Mg and Fe availability when compared to control treatments (*Weete and Walkinshaw,* 1972).

Essential nutrients that might be deficient in lunar soil include N, P, K, and some micronutrients. The small quantities of micronutrients required by plants may make it cost effective to import them from Earth, but macronutrients are required in large quantities. Lunar base fertilizers might, therefore, have to be produced for either soil or hydroponic plant-growing systems (see section on product synthesis).

A possible deterrent to usage of lunar soil for cropping might be the release of heavy metals, especially Ni and Cr, into the bioregenerative system. Constant cropping could also lower lunar soil pH to where Al^{3+} could reduce plant yield. In the soil pH range of 6.0-7.0, the dominant Al solution species would be the nontoxic $Al(OH)_3^0$ rather than Al^{3+} (*Lindsay,* 1979). Liming the soil with lunar fine soil fractions may be one solution. Lunar soil pH in water has never been determined by accepted soil testing methods, but the best available lunar soil simulants have a pH near 8.0. Therefore, the buffering capacity of the lunar fine soil fractions might maintain an adequate pH for cropping and secondary mineral neogenesis.

As on Earth, higher plants would assimilate CO_2. All plants that would be of interest occur in two groupings based on mechanism of CO_2 assimilation. At normal atmospheric CO_2 levels (340 mg l^{-1}), C-4 plants like corn fix CO_2 most efficiently, while at elevated CO_2 levels (1200 mg l^{-1}), C-3 plants like beans would have the advantage in CO_2 fixation due to reduced CO_2 loss via photorespiration (*Black,* 1986).

Initially, N_2 will have to be imported from Earth for generation of an atmosphere. It might be cost effective to generate the majority of plant-available N_2 by symbiotic N_2 fixation. Leguminous species fix atmospheric N_2 when infected with *Rhizobium.* These symbiotic bacteria use plant photosynthate for energy. Symbiotic N_2 fixation was increased fivefold when CO_2 was enriched to 1200 mg CO_2 l^{-1} as compared to fixation at ambient CO_2 levels (*Hardy and Havelka,* 1975). Growing legumes would promote greater usage of the CO_2 available from waste recycling (see section on waste management and utilization), as well as increase the N_2 availability in the soil for subsequent nonlegume crops. Since the volume of N_2 in the lunar base atmosphere is minute when compared to the terrestrial atmosphere, N_2 will have to be added as microorganisms reduce its concentration. Adsorbed on lunar soil surfaces are sources of N_2 and H_2. As H_2 is collected for ilmenite reduction, N_2 might be collected to supplement the lunar base atmosphere.

Implementation

A hypothetical 100 inhabitants would use at least 2100 liters of water daily (*Spurlock and Modell,* 1979), and require a minimum of 600 m^2 of hydroponic food production area (*Salisbury and Bugbee,* 1985). Estimates of food production from lunar soil will not be available until a high-fidelity lunar simulant is available for research. Waste water (water used for all purposes but toilets) could be stored in a fiberglass vessel manufactured from lunar regolith (*Ho and Sobon,* 1979) and supplied to plants growing in lunar soil through a drip irrigation system.

To prevent water loss, lunar soil will have to be confined within a fiberglass containment structure. Lunar minerals are anhydrous and would initially require substantial water. Without containment, water should disperse throughout the soil. Since 85% of crop plant roots are in the top 0.15 m of soil, container depths of 0.6 m should be sufficient for total root proliferation. On the soil surface, CO_2 could be applied through vented piping to maintain at least 1200 and 340 mg CO_2 l^{-1} within the C-3 and C-4 crop canopies, respectively. Approximately 100 kg of CO_2 will be respired per 100 occupants per day in the lunar base (*MacElroy et al.,* 1985). Maximally, C-3 plants can fix 60 μmol CO_2 sec^{-1} m^{-2} when neither light nor CO_2 is limiting (*Challa and Schapendonk,* 1986). This translates to 136 kg of CO_2 fixed per day per 600 m^2. Calculations indicate that 600 m^2 of mature crops, photosynthesizing at theoretical maximum limits, could recycle the CO_2 produced by 100 occupants. Assuming a one-to-one relationship between CO_2 fixation and plant dry weight, and a per person food requirement of 0.6 kg day^{-1} (*MacElroy et al.,* 1985), then daily respiration from 100 occupants plus the average daily CO_2 generated from waste recycling, would supply the minimum food requirements if the crop harvest index is at least 34%. Plant species, planting density, and crop stress levels will of course influence these calculations.

Anaerobically digested plant biomass and sewage sludge residues (see section on waste management and utilization) will be applied to the soil to aid in moisture retention, increase particle aggregation and soil structuring, and subsequently soil gaseous exchange. Select groups of introduced heterotrophic microorganisms could aid in the mineralization of N, P, and micronutrients from organic substrates. Introduced chemoautotrophic microbes could aid in the conversion of ions to a more plant-preferred ionic species. Algae could be applied to the soil surface to reduce gaseous N losses (*Alexander,* 1977).

Soil-water relationships will be of extreme importance. The approximate bulk density of lunar soil is 1.5 g cm^{-3} (*Carrier et al.,* 1973). With a cropping area of 600 m^2 and a depth of 0.6 m, the soil would weigh 540,000 kg by terrestrial standards. Terrestrial basalt, ground to approximate particle size of lunar samples, has a water holding capacity of 4.3% at 0.33 bar as determined by the pressure membrane extraction technique (G. W. Easterwood, unpublished data, 1988). Assuming the same water-holding capacity, lunar soil by weight could contain at least 23,220 liters of water, equivalent to the waste water of 100 occupants for 10 days. Soil moisture content could be monitored with a neutron probe at various depths to ensure optimal moisture and aeration for plant roots.

Most of the water applied to the cropping area will be transpired into the atmosphere, reclaimed by condensation, distilled for purification, and stored directly in the potable water storage tank. Plants transpire approximately 225 kg of H_2O per kilogram dry weight biomass produced (*Salisbury and Ross,* 1978). Wheat, for example, with a life cycle of 60 days and biomass production of 3120 kg on 600 m^2 of cropping area (*Salisbury and Bugbee,* 1985), would transpire an average of 11,700 liters of H_2O per day.

Crops transpire more than three times the occupant water requirements, leaving surplus potable water that could be used for fish production. With intensive aquacultural practices, it is possible to produce 200 kg of fish m^{-3} of water per year (*Balarin and Haller,* 1983). A tank containing 8400 liters of water (11,700

total from plant transpiration—3000 for occupants, 300 for solid waste transportation) could produce 16,800 kg of fish annually. Fish, like tilapia (*Tilapia aurea*), can feed on processed plant biomass. Possibly some of the crop biomass or residual solid from the anaerobic digestion process could be processed for fish food (*Degani et al.*, 1983). To reduce the buildup of toxic compounds from fish excrement, waste water can be recycled through the soil system providing supplemental N_2 fertilization to growing plants. Solid wastes may be removed from the water and combined with the human biological wastes.

WASTE MANAGEMENT AND UTILIZATION

Wastes, defined as biomass from crops and the solid, liquid, and gaseous biological wastes from the occupants, will be important sources of recycled CO_2, H_2, O_2, N_2, P, K, and energy within the lunar base ecosystem. Of the wastes that will be produced, gases such as CO_2 will be removed during atmospheric recycling through the crop growing area. Waste water will be recycled by transpiration through the soil-plant system. Daily production of occupant solid waste will average 109 g dry weight of feces per person (*MacElroy et al.*, 1985), and 2340 kg of dry weight inedible plant biomass per 60 days on 600 m^2 of growing area, assuming wheat production of 1.3 kg seed m^2 with a harvest index of 0.25 (*Salisbury and Bugbee*, 1985).

Solids will be recycled by biological conversion processes. Biological conversion of solid wastes will be more suitable for energy extraction and nutrient recycling than will thermal conversion (*Chynoweth*, 1987). Anaerobic digestion of the biomass will produce CH_4 and CO_2 gases, and a residual concentration of N, P, and K in the digestion effluent. Utilizing the latest technology in anaerobic digestion design, 92% conversion of biodegradable substrates (1:1 ratio of sludge:plant biomass) into gaseous products may be obtained with a loading rate of 91 g of dry weight biomass per 28.32 liters of digester volume per day. Total gas yield is 780 liters per kilogram of dry weight volatile solids (*Gas Research Institute et al.*, 1986).

Implementation

Sewage plumbing will be independent from waste water plumbing. Following a toilet discharge, sewage will pass through a macerator to reduce particle size prior to storage. Small biomass particle size lowers retention time within the anaerobic digester and facilitates greater degradation. Inedible crop biomass can also be milled and stored separately for future anaerobic decomposition.

Optimal ratios of sewage to plant biomass will be pumped from the storage tanks and combined within an anaerobic digester(s) for degradation of materials and generation of gases and nutrients. Products of the anaerobic digestion are gases (64% CH_4 and 36% CO_2 per unit volume) and liquid effluent containing N, P, and K. Approximate nutrient concentrations in the effluent after digestion of water hyacinths, for example, were 289 mg $NH^{4+}\,l^{-1}$, 12 mg $P\,l^{-1}$, and 123 mg $K\,l^{-1}$ (*Reddy*, 1988). Gases will be separated and stored. Residual solids can be applied to amend the soil or used as fish feed (*Degani et al.*, 1983). Solid-free digestion effluent that emerges from the digester essentially sterile (*National Academy of Sciences*, 1977) may be mixed with waste water to produce a suitable fertilizer for crops through the drip irrigation system.

PRODUCT SYNTHESIS

The major products that must be produced on the Moon are oxygen and water. Water could be generated from the reduction of ilmenite with H_2, and O_2 produced from sequential electrolysis (*Gibson and Knudsen*, 1985; *Williams*, 1985). Since a hydrogen sink exists in water production, resupply of H_2 will be imperative. Methane from anaerobic digestion may be processed to produce H_2 and CO_2. Direct reduction of ilmenite with methane has also been studied by Russian scientists (*Reznichenko et al.*, 1983).

During crop production on the Moon, a phosphate sink may develop that would require input into the system. Orthophosphate ions are very reactive and relatively immobile in soils. Once applied, orthophosphate may be adsorbed to mineral surfaces and/or precipitated from solution as an insoluble Ca, Fe, or Al phosphate (*Tisdale and Nelson*, 1975). In extremely unfavorable environments, up to 90% of applied fertilizer $H_2PO_4^-$ is unavailable to plants from "fixation" mechanisms (*Stevenson*, 1982). Trace quantities of apatite and whitlockite minerals exist within the lunar regolith (*Williams and Jadwick*, 1980) and may provide the balance of deficient quantities of orthophosphate. Mining these minerals for P may be as essential to lunar agriculture as mining ilmenite will be for water and oxygen production. To produce water-soluble fertilizers, however, strong acids will have to be produced. Complex fertilizer technology for processing lunar regolith could only exist within a well-established and self-sustaining lunar base.

Implementation

Methane, produced from the anaerobic digestion process, will have to be separated from CO_2 for generation of H_2 or direct reduction of ilmenite with CH_4. Conventional separation of CO_2 and H_2S from CH_4 may be accomplished by the Girbotol or Monoethanolamine process (*Shreve*, 1967). Concentrations of less than 0.01% CO_2 by volume in the H_2 gas may be obtained by this regenerative method. Hydrogen gas may be synthesized by the Steam-Hydrocarbon Reforming process (*Shreve*, 1967), which chemically processes CH_4 into CO_2 and H_2. Again, the Girbotol process could be employed to remove CO_2. Since temperatures fluctuate between 102K and 384K during the 14-Earth-day lunar day and 14-Earth-day lunar night, cryogenic methods of gas separation may provide a low-energy alternative compared to chemical methods.

From sewage and crop biomass, approximately 18,018 kg (14,040 kg from 6 cropping periods on 600 m^2 and 3978 kg from feces of 100 occupants) of dry weight wastes should be generated per year. With a 92% solid waste bioconversion efficiency, and 780 liters of gas generated per kilogram of solid, with 64% of the gas CH_4, approximately 8,275,018 liters of CH_4 would be produced annually. Assuming 100% efficiency during the steam-hydrocarbon reforming process, and reduction of ilmenite without any losses or inputs into either process, approximately 13,400 liters of water could be produced. Direct reduction of ilmenite with CH_4 might reduce the number of intermediate steps and energy requirements.

INTEGRATING A SYSTEM: FARMING, WASTE MANAGEMENT, AND PRODUCT SYNTHESIS

This paper attempts to integrate the interdependent components of food production, waste management and utilization, and

product synthesis into a theoretical working regenerative system that could support a lunar base. Each component with respect to the terrestrial environment has been studied extensively, but their integration for maintenance of life support systems has never been attempted.

Crops with different mechanisms of CO_2 fixation should be grown in separate greenhouse modules so that maximal yield can be obtained in association with life support requirements. For example, lunar base atmosphere may be cycled through an agricultural module with C-4 plants such as corn, whose CO_2-fixing enzyme possesses a high affinity for CO_2. Another module containing plants with the C-3 pathway of CO_2 fixation could best utilize the elevated crop canopy CO_2 concentrations from CO_2 generated by the anaerobic digestion process. Crop rotation within agricultural modules will be important as leguminous crops fix N_2 in the soil for subsequent use by nonleguminous crops. The modular concept would not only permit easy expansion of crop production area with lunar base growth and development, but would also provide isolation of possible plant pathogens if crops encounter disease.

Agricultural modules will probably have to be covered with lunar regolith for radiation shielding. Plants grow well under artificial lighting, but supplying lamps from Earth would be prohibitive. Advances are occurring in light pipe and fiber optic technologies that may permit piping in selected wavelengths of sunlight. Also, a whole series of crop cultivars, adapted to the lunar day/night cycle, may have to be developed.

Advanced sensor technology coupled to artificial intelligence systems will control environmental parameters such as light intensity, temperature, soil moisture, relative humidity, and CO_2 and O_2 concentrations. Computerized infrared camera systems will scout for and identify causes of plant stress. "Smart" robots will be used to plant, cultivate, and harvest crops to provide a mission specialist adequate time for experimentation. After harvest, edible crop portions can be sent to a centralized processing and storage center. Transpiration water, reclaimed by consendation and distilled, can be stored in the potable water storage tank. Waste water, generated from lunar base occupants and aquacultural systems, will be stored, mixed with digester effluent, and applied to the soil-plant system through drip irrigation. A portion of the crop biomass, after milling, can be used for fish feed and the remainder sent to a centralized waste control center for anaerobic digestion.

At the waste control center, proper ratios of sewage and biomass can be mechanically mixed and injected into anaerobic digesters. Processed digester effluent can be transported to the agricultural modules for mixing with waste water. Residual digester solids may be used as fish feed (*Degani et al.,* 1983) or applied to the soil-plant system. A flow chart of ecosystem wastes and water is given in Fig. 1. Gases from anaerobic digestion may be segregated and processed to produce H_2. Carbon dioxide, collected during processing, will be returned to the C-3 greenhouse module. Hydrogen product gas will be sent to mining operations for the reduction of ilmenite.

CONCLUSIONS

Conservation and recycling of all solids, liquids, and gases within a bioregenerative lunar base will be of extreme importance. A closed loop Controlled Ecological Life Support System must be designed around food production, waste management and utilization, and product synthesis.

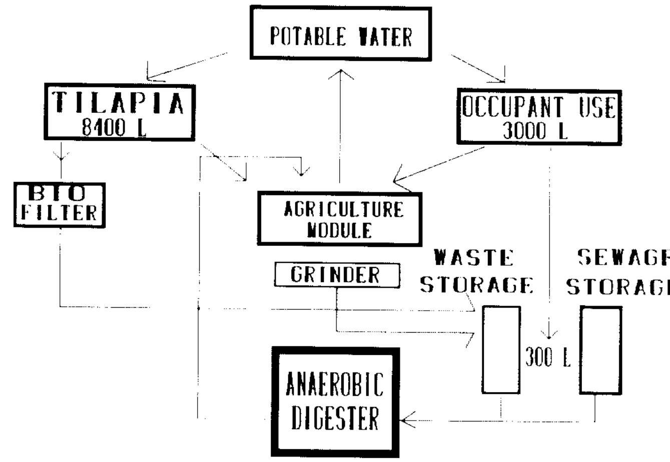


Fig. 1. Theoretical flow chart of wastes and water in lunar base CELSS.

REFERENCES

Alexander M. (1977) *Introduction to Soil Microbiology.* Wiley, New York. 467 pp.

Balarin J. D. and Haller R. D. (1983) Commercial tank culture of tilapia. *Proc. Int. Symp. on Tilapia in Aquaculture,* pp. 473-483.

Black C. C. Jr. (1986) Effects of CO_2 concentration on photosynthesis and respiration of C_4 and CAM plants. In *Carbon Dioxide Enrichment of Greenhouse Crops, Vol. 2* (H. Z. Enoch and B. A. Kimball, eds.), pp. 29-40. CRC Press, Boca Raton, Florida.

Burden D. and Angelo J. A. Jr. (1985) Nuclear energy—Key to lunar development. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 85-98. Lunar and Planetary Institute, Houston.

Carrier W. D. III, Mitchell J. K., and Mahmood A. (1973) The nature of lunar soil. *J. Soil Mech. Found. Div., 99,* 813-832.

Challa H. and Schapendonk A. H. C. M. (1986) Dynamic optimalization of CO_2 concentration in relation to climate control in greenhouses. In *Carbon Dioxide Enrichment of Greenhouse Crops, Vol. 1* (H. Z. Enoch and B. A. Kimball, eds.), pp. 147-160. CRC Press, Boca Raton, Florida.

Chynoweth D. P. (1987) Biomass conversion options. In *Aquatic Plants for Water Treatment and Resource Recovery* (K. R. Reddy and W. H. Smith, eds.), pp. 621-642. Magnolia Publishing, Orlando, Florida.

Degani G., Levanon D., and Marchaim U. (1983) Substitution of digested slurry (composed of fermented human waste, cow manure, and straw) added to the culture tank for *Oreochromis aureus* food. *Proc. Int. Symp. on Tilapia in Aquaculture,* pp. 366-373.

Duke M. B., Mendell W. W., and Roberts B. R. (1985) Strategies for a permanent lunar base. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 57-68. Lunar and Planetary Institute, Houston.

Gas Research Institute, Institute of Gas Technology, Reedy Creek Utilities Co., University of Florida-Institute of Food and Agricultural Sciences, and Walt Disney Imagineering (1986) *Community Waste Research at the Walt Disney World Resort Complex.* Walt Disney Company, Lake Buena Vista, Florida. 19 pp.

Gibson M. A. and Knudsen C. W. (1985) Lunar oxygen production from ilmenite. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 543-550. Lunar and Planetary Institute, Houston.

Hardy R. W. F. and Havelka U. D. (1975) Photosynthate as a major factor limiting nitrogen fixation by field grown legumes with emphasis on soybeans. In *Symbiotic Nitrogen Fixation in Plants* (P. S. Nutman, ed.), pp. 421-439. Cambridge, New York.

Ho D. and Sobon L. E. (1979) Extraterrestrial fiberglass production using solar energy. In *Space Resources and Space Settlements* (J. Billingham, W. Gilbreath, and B. O'Leary, eds.), pp. 225-232. NASA SP-428.

Keller W. D. and Huang W. H. (1971) Response of Apollo 12 lunar dust to reagents simulative of those in the weathering environment of earth. *Proc. Lunar Sci. Conf. 2nd,* pp. 973-81.

Lindsay W. L. (1979) *Chemical Equilibria in Soils.* Wiley, New York. 449 pp.

MacElroy R. D., Klein H. P., and Averner M. M. (1985) The evolution of CELSS for lunar bases. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 623-634. Lunar and Planetary Institute, Houston.

National Academy of Sciences (1977) *Methane Generation from Human, Animal, and Agricultural Waste.* National Research Council, Washington, DC. 131 pp.

Reddy K. R. (1988) Water hyacinth (*Eichbornia crassipes* (Mart) Solms) biomass cropping systems: I. Production. In *Methane from Biomass: A Systems Approach* (W. H. Smith and J. R. Frank, eds.), pp. 103-140. Elsevier, New York.

Reznichenko V. A., Galushoko Yu. S., Karyazin I. A., and Moorazov A. A. (1983) Mechanism of fluidization, heating, and reduction of iron-titanium concentrates in a fluidized bed by gases containing methane. *Izv. Akad. Nauk. S.S.S.R., Mettally., 6,* 9-14.

Salisbury F. B. and Bugbee B. G. (1985) Wheat farming in a lunar base. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 635-646. Lunar and Planetary Institute, Houston.

Salisbury F. B. and Ross C. W. (1978) *Plant Physiology,* 2nd edition. Wadsworth, Belmont, California. 422 pp.

Shreve R. N. (1967) *Chemical Process Industries,* 3rd edition. McGraw-Hill, New York. 905 pp.

Spurlock J. and Modell M. (1979) Systems engineering overview for regenerative life-support systems applicable to space habitats. In *Space Resources and Space Settlements* (J. Billingham, W. Gilbreath, and B. O'Leary, eds.), pp. 1-11. NASA SP-428.

Stevenson F. J. (1982) *Humus Chemistry: Genesis, Composition, Reactions.* Wiley, New York. 443 pp.

Tisdale S. L. and Nelson W. L. (1975) *Soil Fertility and Fertilizers,* 3rd edition. Macmillan, New York.

Weete J. D. and Walkinshaw C. H. (1972) Apollo 12 lunar material: Effects on plant pigments. *Can. J. Bot., 50,* 101-104.

Williams R. J. (1985) Oxygen extraction from lunar materials: An experimental test of an ilmenite reduction process. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 551-558. Lunar and Planetary Institute, Houston.

Williams R. J. and Jadwick J. J., eds. (1980) *Handbook of Lunar Materials.* NASA RP-1057.

CROP GROWTH AND ASSOCIATED LIFE SUPPORT FOR A LUNAR FARM

N93-13994

Tyler Volk

Earth Systems Group
Department of Applied Science
New York University
New York NY 10003

Hatice Cullingford

Lunar and Mars Exploration Program Office
NASA Johnson Space Center
Houston TX 77058

Supporting human life on a lunar base will require growing many different food crops. This paper investigates the growth dynamics of four crops (wheat, soybeans, potatoes, and lettuce) for general similarities and differences, along with associated material flows of the gases, liquids, and solids in a lunar farm. The human dietary requirements are compared with the protein, carbohydrate, and lipid contents of these hydroponically grown, high-productivity crops to derive a lunar farm diet. A simple and general analytical model is used to calculate the mass fluxes of CO_2, H_2O, HNO_3, and O_2 during the life cycle of each of the four crops. The resulting farm crop areas and corresponding biomass production rates are given. One significant conclusion of this study is that there is a "lipid problem" associated with the incorporation of these four crops into a viable diet.

INTRODUCTION

Following the return of our astronauts to the lunar surface around the turn of the twenty-first century, an outpost for temporary habitation could evolve into a permanently occupied base on the Moon (*Ride*, 1987). The major human life support needs will have to be met at increasingly self-sufficient rates during this evolution. The pathways leading to a lunar farm are yet to be defined in the habitat development scenarios.

Human diets for a lunar base can be provided with hundreds of foods. Here, however, we will focus on four crops studied in the NASA Controlled Ecological Life Support Systems (CELSS) Program: lettuce, potatoes, soybeans, and wheat. Substantial data have been generated on the response of these crops to variables important in future space agriculture such as near-maximally achievable planting density, light intensities and schedules, and atmospheric CO_2 levels. Additional experimental data for these crops were received in 1987 through personal communication with CELSS researchers B. Bugbee, C. Mitchell, D. Raper, R. Wheeler, and S. Schwartzkopf. Information received included environmental conditions for both the aerial and root plant parts in particular high-yield experiments. Figure 1a shows the composition of the edible portions of lettuce, potatoes, soybeans, and wheat in terms of the three major food types, protein, carbohydrate, and lipid.

To incorporate these crops into a farm, we consider the dietary needs that must be met by the candidate crops. Figure 1b shows the protein, carbohydrate, and lipid requirements of two standard satisfactory diets. More detailed dietary breakdowns, such as essential amino acids, fatty acids, and vitamins are beyond the scope of this study. Even though each diet provides 2700 kcal per day per person, the relative fractions of calories obtained from proteins and lipids are different. By comparing the compositions of the crops (Fig. 1a) with those of the diets (Fig. 1b), a lipid problem becomes evident.

The lipid problem arises because both standard diets contain more lipid than protein. Diets with lower lipid than those used here might be desirable (*Roberts*, 1988). Because none of the four crops contains more lipid than protein, any allotment we make using these crops to fulfill the total lipid requirements will concomitantly have an excess of protein. Waste such as this would be detrimental to a space agriculture prescribed by energy and mass constraints.

CROP MODEL DEVELOPMENT

Simulation models help us conceptualize and design new systems by using a mathematical framework to assemble components for investigating specific system-level issues. Previous work along these lines developed a model (called BLSS) for a CELSS that grows wheat as the sole crop (*Volk and Rummel*, 1987; *Rummel and Volk*, 1987). BLSS can be used to track the flow of carbon, hydrogen, oxygen, and nitrogen through the various processes in a CELSS because it contains the stoichiometries for various compounds such as plant protein and human urine. The model grows wheat in a variety of planting schemes, with different numbers and sizes of simultaneous batches. Different schemes produce different magnitudes of fluctuations in the standing biomass and in the buffer mass reservoirs of CO_2, H_2O, HNO_3, and O_2.

Here we extend this approach to include lettuce, potatoes, and soybeans also. Figure 2, along with the model results still to be discussed, shows selected and typical data for the growth of the edible and inedible parts (to humans) of each crop. A breakdown of biomass into edible and inedible parts is fundamental in a CELSS because of the consequent separation of material flows.

Many crop growth curves prominently show an S-shaped or sigmoidal curve typical of biological systems. The logistic differential equation $dC/dt = rC(1-C/K)$ imitates this S-shape of exponential growth followed by a leveling off. The term C is

biomass, t is time, r is growth rate for the purely exponential part of the system, and K is a "negative feedback" from the growth process itself, an environmentally modifiable but inherent (genetically based) slowing of the total growth rate (dC/dt) by the approach of the crop to its mature size. The logistic equation thus contains some biologically meaningful parameters and is chosen to represent the growth of the inedible crop parts.

The equation for the edible crop parts must be somewhat differently structured. The edible cells, like the inedible ones, reproduce, so the total edible growth is set proportional to the edible mass. Furthermore, the nonphotosynthesizing edible parts (except for lettuce; see below) grow using products from photosynthesis by the inedible parts (the leaf mass); therefore, the inedible biomass (M_{ined}) should also appear in the edible equation. Also, the edible growth occurs substantially after the beginning of the inedible growth (see Fig. 2), so a switch-on time (t^*) is used in the formulation for edible growth. The edible biomass (M_{ed}) is assumed to be equal to zero before t^* and to start its growth at t^* with minimum edible mass (E_{min}). With these considerations we write

$$\text{all } t: \quad \frac{dM_{ined}}{dt} = r_{ined} M_{ined}\left(1 - \frac{M_{ined}}{K_{ined}}\right) \tag{1a}$$

$$t < t^*: \quad \frac{dM_{ed}}{dt} = 0 \tag{1b}$$

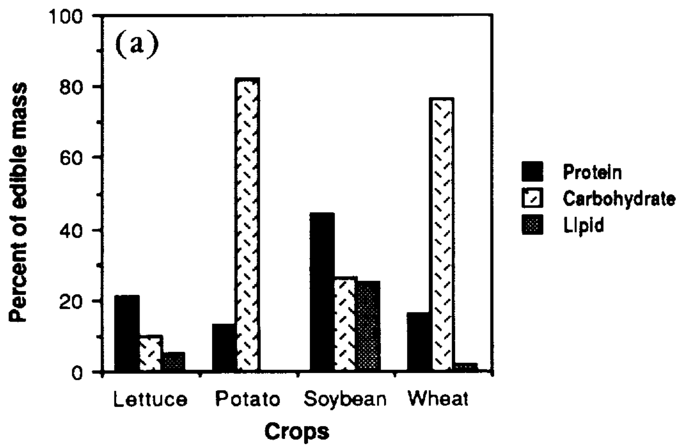
$$t \geq t^*: \quad \frac{dM_{ed}}{dt} = r_{ed} M_{ined}\left(\frac{E_{min} + M_{ed}}{K_{ed}}\right)\left(1 - \frac{M_{ed}}{K_{ed}}\right) \tag{1c}$$

The parameters t and t^* are in units of time, while r_{ined} and r_{ed} in time^{-1} and the remainder in mass (see Table 1). For wheat, soybean, and potato we use equations (1a) to (1c). Because the edible and inedible parts develop together, the parameter t^* is defined differently for lettuce. *Mitchell et al.* (1986) found that the growth rate increases by more than a factor of two at about 11 days; therefore we define $r_{ed,2}$ and $r_{ed,1}$ for $t > t^*$ and $t < t^*$, respectively. The equations become for lettuce

$$t < t^*: \quad \frac{dM_{ed}}{dt} = r_{ed,1} M_{ed}\left(1 - \frac{M_{ed}}{K_{ed}}\right) \tag{2a}$$

$$t \geq t^*: \quad \frac{dM_{ed}}{dt} = r_{ed,2} M_{ed}\left(1 - \frac{M_{ed}}{K_{ed}}\right) \tag{2b}$$

$$\text{also} \quad \frac{dM_{ined}}{dt} = \frac{dM_{ed}}{dt}\frac{K_{ined}}{K_{ed}} \tag{2c}$$



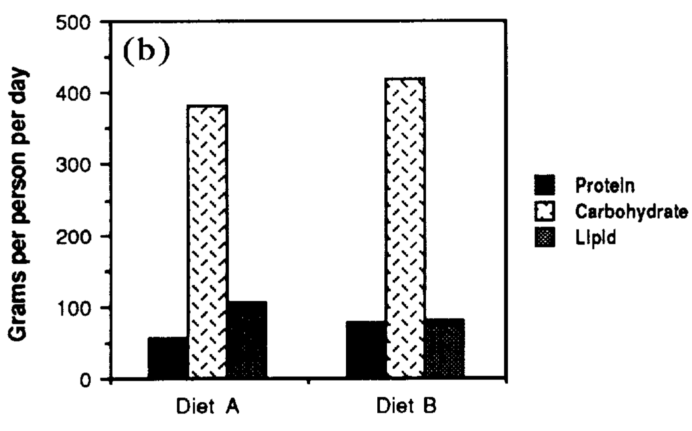


Fig. 1. **(a)** Compositions of lettuce leaves, potato tubers, soybeans, and wheat berries for typical high-yield hydroponic growth experiments. Data provided by CELSS researchers C. Mitchell (lettuce), R. Wheeler (potatoes), D. Raper (soybeans), and from *Bugbee and Salisbury* (1988, wheat). The balancing components of fiber and ash are not shown. **(b)** Compositions of two possible diets. Diet A is from the 1980 Recommended Dietary Allowances and Estimated Safe and Adequate Daily Dietary Intake, using American Heart Association recommendations of 35% of food kcal from fat (*Krause and Mahan,* 1980). Diet B uses the NIH recommendations (C. Mitchell, personal communication, 1988) of 0.5 g protein per day per lb of body mass and using lower value of the recommended 30-50% of nonprotein food kcal as lipid to give lower lipid, higher protein diet to contrast with diet A. Both diets are approximately for a 155-lb individual having 2700 kcal per day.

These models were run in a computer program and the results generated were compared to the experimental crop data. Adjustments were made to the parameters until the models agreed reasonably with the data. The parameters used for each crop are listed in Table 1, while the model outputs are shown in Fig. 2.

The output curves demonstrate that it is relatively easy to represent the data with a model whose parameters have some fundamental biological meaning. Table 1 lists the actual planting mass for the crops, but we need to investigate further the data at t = 0 to determine whether they correspond to the initiation of the crop from seed or tissue or to the transplanting time after initial seeding growth. Some further adjustment might be necessary to account for the physical meaning of time t = 0.

Additional refinements are possible. Better fits to the growth curves shown for wheat and potatoes in Fig. 2 are obtainable. More importantly, the model parameters, such as growth rates

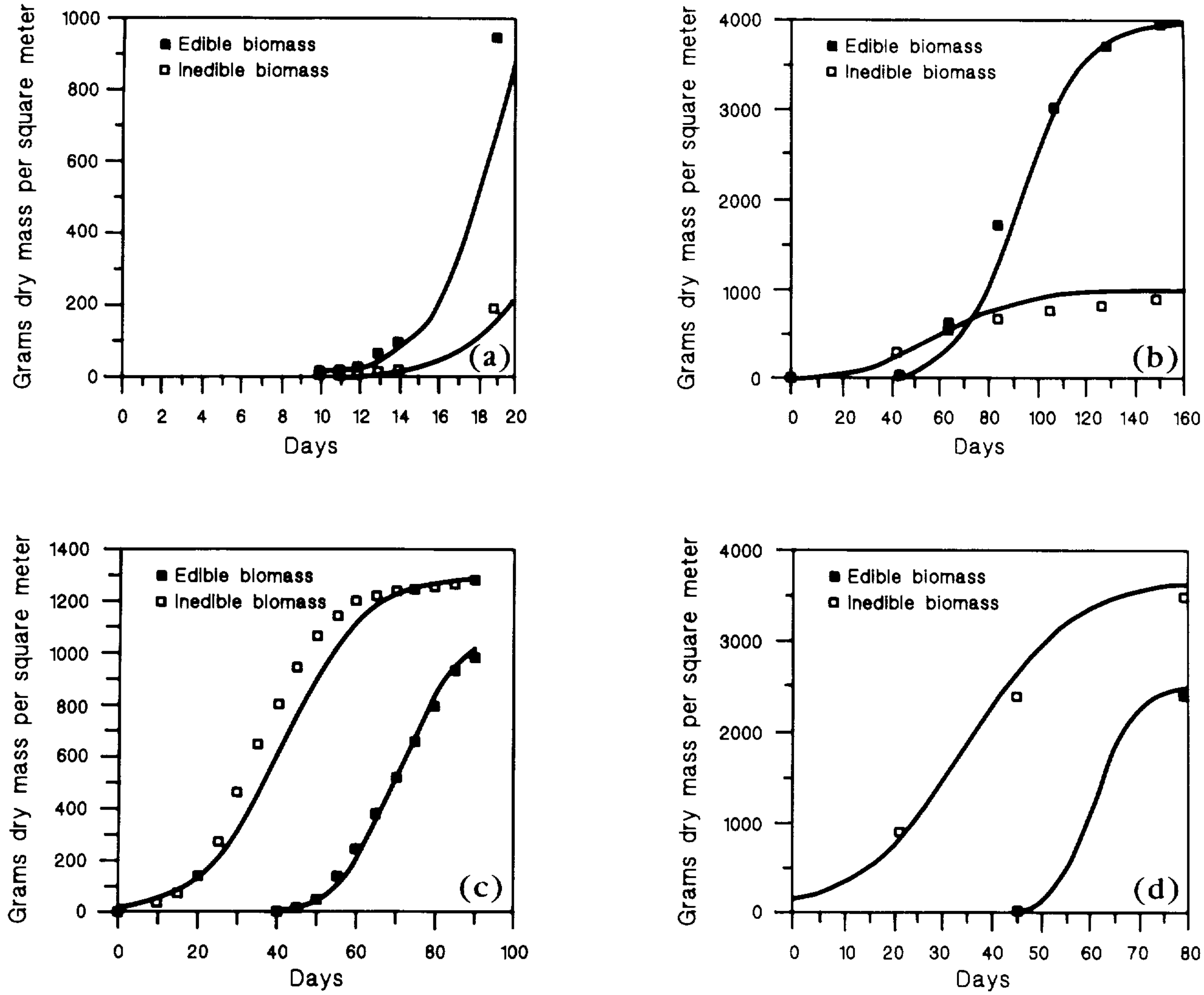


Fig. 2. Models of crop growth using parameters from Table 1, compared to crop growth data. **(a)** Lettuce data are from *Mitchell et al.* (1986) at 1000 ppm CO_2 and 450 μmol/m^2-sec of PPF [data were given per plant and adjusted here to yield leaf production of 60 g/m^2-d (C. Mitchell, personal communication, 1987)]. **(b)** Potato data are from *Wheeler and Tibbitts* (1987) for dry mass production under 24-hour continuous light at 300 μmol/m^2-sec PPF (assume 5 plants per m^2). **(c)** Soybean data are from D. Raper (personal communication, 1987) grown at 700 μmol/m^2-sec PPF and 400 ppm CO_2 (data were interpolated by D. Raper to be in equal time intervals). **(d)** Wheat data are from B. Bugbee (personal communication, 1987) for plants grown at 1200 μmol/m^2-sec and 1200 ppm CO_2 (see also *Bugbee and Salisbury,* 1988). Data represent individual growth experiments, not necessarily the maximum yields ever obtained. Model parameters were not adjusted to achieve exact fits to growth data, rather to demonstrate the utility of equations (1) and (2) in providing a relatively simple method of generating growth curves to determine gas and fluid fluxes applicable for including plants in systems models.

TABLE 1. Parameters for crop models.

Parameter	Wheat	Soybean	Potato	Lettuce
r_{ined} (day^{-1})	0.09	0.10	0.06	same as r_{ed}
r_{ed} (day^{-1})	0.17	0.10	0.30	$r_{ed,1} = 0.2$, $r_{ed,2} = 0.5$
K_{ined}	3700.0	1300.0	1000.0	1000.0
K_{ed}	2500.0	1100.0	4000.0	5000.0
E_{min}	80.0	80.0	400.0	X
$M_{ined,o}$	150.0	20.0	25.0	X
$M_{ed,o}$	0.0	0.0	0.0	2.0
t^* (days)	45.0	45.0	40.0	11.0

Units for K_{ined}, K_{ed}, E_{min}, $M_{ined,o}$, $M_{ed,o}$ are g dry mass m^{-2}.

(r_is) and ultimate biomass (K_is), are not constant, but are functions of environmental conditions. A reasonable approach could be to develop these parameters along the lines of classical mathematical treatments of photosynthesis, such as in *Gates* (1980), wherever possible. That way the data would not be used for fitting, but rather for model validation. Transpiration submodels and the relationships between atmospheric pCO_2, humidity, nutrient uptake, and biomass growth need to be developed for investigation of the various design tradeoffs between energy, mass, and volume. The models shown here would serve as a basis for further developments.

Volk and Rummell (1987) listed formulas for protein, carbohydrate, lipid, fiber, and lignin that can be placed into

C-3

balances equations containing carbon, hydrogen, oxygen, and nitrogen. It is therefore possible to calculate the uptake of CO_2, H_2O, and HNO_3, and the production of O_2 by the crops. These compounds vary as a function of fractional distribution of protein, carbohydrate, lipid, fiber, and lignin in the biomass. Table 2 shows the mass balances for the four crop models. For example, note the substantial differences between soybean and wheat in the CO_2 required and the O_2 produced per gram of edible biomass produced. This difference is due primarily to the difference in lipid content. There are corresponding differences in the fluxes of these materials between the crops and their environments. These fluxes are important in the design of engineered hardware for the various crops.

The balances in Table 2 were used with the crop growth models to calculate the fluxes of CO_2, H_2O, HNO_3, and O_2 during growth; these fluxes are shown in Fig. 3. Note the different curves for the crops. Such curves will be produced during the actual operation of a CELSS (e.g., if CO_2 will be monitored and maintained at desired levels in the crop's atmosphere, the amount of CO_2 injected to maintain these levels will be known). Due to the characteristic patterns of these fluxes, it is possible to relate this information to the monitoring system for the state of the whole crop. Note that these curves assume a constant percentage of protein, carbohydrate, lipid, fiber, and lignin for the edible and

TABLE 2. Mass balances for crop models.

Mass Types	Wheat	Soybean	Potato	Lettuce
Edible Mass Fractions				
Protein	0.17	0.45	0.13	0.26
Digestible Carbohydrate	0.78	0.30	0.84	0.12
Lipid	0.02	0.25	0.00	0.06
Fiber	0.03	*	0.03	0.56
Lignin	0.00	*	0.00	0.00
Fluxes During Edible Biomass Production (g per g dry biomass)				
CO_2 (in)	1.62	2.10	1.57	1.82
H_2O (in)	0.59	0.66	0.58	0.57
HNO_3 (in)	0.13	0.34	0.10	0.20
O_2 (out)	1.34	2.11	1.26	1.59
Inedible Mass Fractions				
Protein	0.09	0.17	0.19	0.11†
Digestible Carbohydrate	0.14	0.80	0.30	0.11†
Lipid	0.00	0.03	0.00	0.00†
Fiber	0.72	*	0.45	0.78†
Lignin	0.05	*	0.06	0.00†
Fluxes During Inedible Biomass Production (g per g dry biomass)				
CO_2 (in)	1.72	1.63	1.75	1.68
H_2O (in)	0.56	0.59	0.56	0.55
HNO_3(in)	0.07	0.13	0.14	0.08
O_2 (out)	1.35	1.36	1.45	1.32

* Fiber and lignin were included in the soybean carbohydrate data.
† Values assumed by T. Volk.

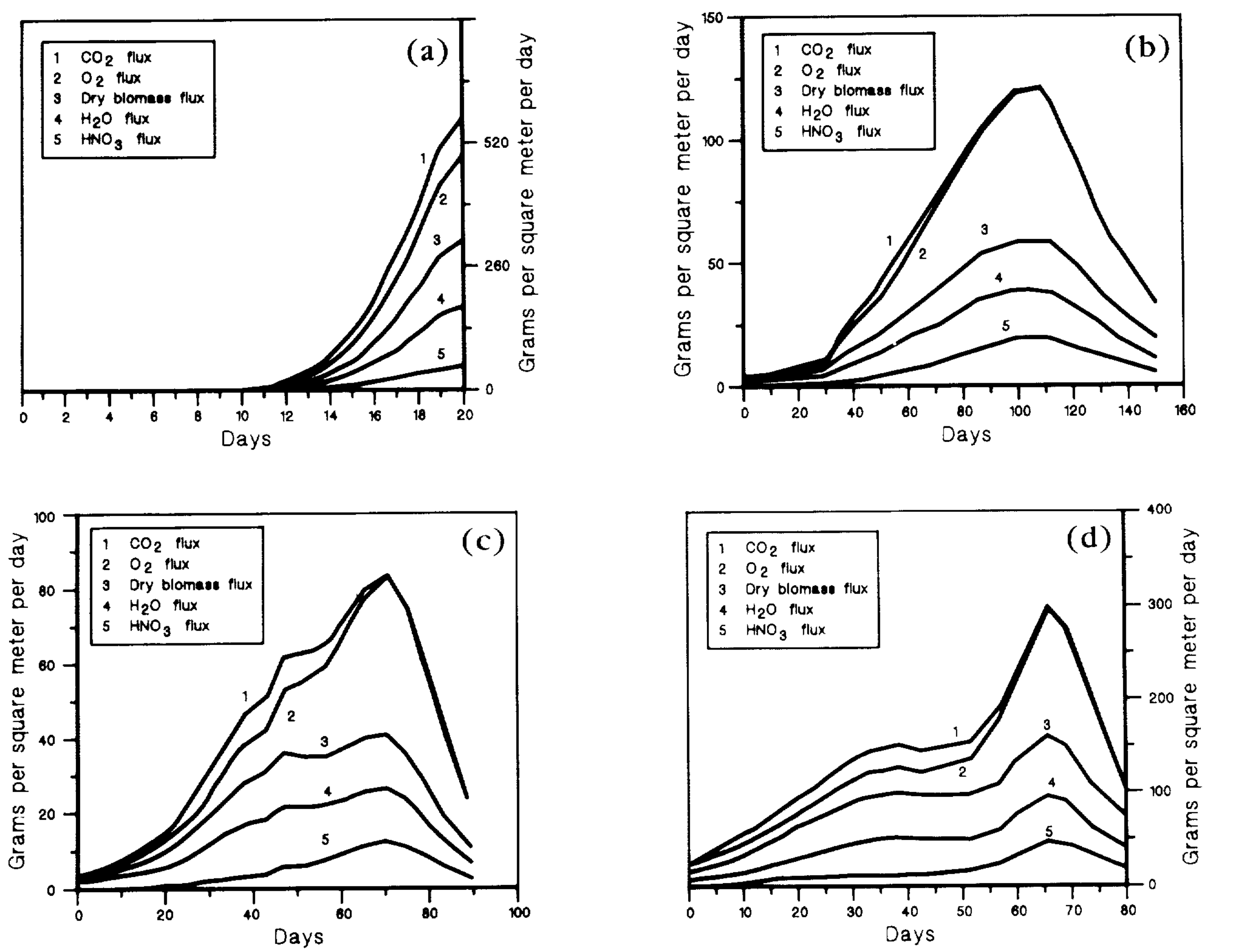


Fig. 3. Fluxes of CO_2, metabolic H_2O, nutrient HNO_3, O_2 produced, and total dry weight biomass (edible plus inedible) for the four crop models: **(a)** lettuce; **(b)** potato; **(c)** soybean; and **(d)** wheat. Note different units for the different crops. Fluxes are from the models of Fig. 2 using the stoichiometries of Table 2.

inedible during their respective growths. That this is clearly not the case is seen in the decrease in leaf N during the seed growth in the hydroponic wheat (*Bugbee and Salisbury*, 1988). A next step here would be to let this N change represent a decrease in the protein of the edible parts during the late state of growth and to see how much this decrease affects the CO_2, H_2O, HNO_3, and O_2 fluxes.

LUNAR FARM DISCUSSION

The crops can be incorporated into a collective model for the entire farm, assuming the relative areas and volumes for each crop are known. We now assemble the four crops into a diet following a particular logic. We first assume that a person could consume 10 g of dry biomass of lettuce leaf per day. Furthermore, to use all four crops and take advantage of the complete protein created by the combination of grains (wheat) and legumes (soybean), we assume equal contributions from potatoes, wheat, and soybean to meet the daily protein requirements. After satisfying the protein requirements, the next critical component is lipid. The only crop with substantial lipid is soybean, so additional soybean is added to bring the total lipid up to the target values for the two diets. All these results are summarized in Table 3.

The protein and lipid requirements are now satisfied, but carbohydrate is still short. Potatoes have a significant fraction of carbohydrate, with a ratio of carbohydrate to protein approximately the value required by the diets. The final step in forming the diet, therefore, is to add potatoes until the target value for carbohydrate is reached; but this adds still more protein. As seen in Table 3, the mix of crops to yield 100% of the target values for protein and lipid results in an excess of protein, with total protein now about 400% and 250% of the respective requirements for diets A and B.

By considering the areas required to grow each crop, the total farm area for the life support system can be estimated (see Table 4). The per-area productivity for each crop used in this computation was taken from the data used in Fig. 2. Note that some of these crops have been grown at higher productivities; wheat, for example, has been grown at double the productivity shown by increasing the light level (*Bugbee and Salisbury*, 1988). Thus higher light levels might yield still higher productivities. Light will probably be a useful control parameter for temporarily increasing the yields following crop failure or equipment downtime when storage reservoirs need increased rates of replenishment. Thus the productivities shown in Table 4 were deliberately chosen not to be the maxima. For one thing, the

TABLE 3. Assembly of a lunar farm diet with four crops.

Crop	Diet A Protein	Diet A Carbo-hydrate	Diet A Lipid	Diet A Dry Mass	Diet B Protein	Diet B Carbo-hydrate	Diet B Lipid	Diet B Dry Mass	Rationale
Lettuce	2.1	1.0	0.5	10.0	2.1	1.0	0.5	10.0	Assume 10 g dry mass person^{-1} day^{-1}
Potato	18.7	118.0	0.0	143.8	25.8	162.8	0.0	198.5	Assume 1/3 target protein* supplied
Soybean	18.7	11.0	10.6	42.5	25.8	15.2	14.7	58.6	Assume 1/3 target protein supplied
Wheat	18.7	87.7	2.2	114.7	25.8	121.0	3.1	158.3	Assume 1/3 target protein supplied
Soybean	160.9	94.9	91.7	365.7	107.7	63.6	61.4	244.8	Add soy until lipid target†
Potato	11.1	70.4	0.0	85.4	8.6	54.4	0.0	73.8	Add potato until carbohydrate target‡
Total	230.2	383.0	105.0	762.1	195.8	418.0	79.7	744.0	
% target	411	100	100		253	100	100		

*Target values for protein are 56 g day^{-1} for diet A and 77.5 g day^{-1} for diet B (see Fig. 1).
† Target values for lipid are 105 g day^{-1} for diet A and 79.7 g day^{-1} for diet B (see Fig. 1).
‡ Target values for carbohydrate are 383 g day^{-1} for diet A and 418 g day^{-1} for diet B (see Fig. 1).
All values except percentages are in g person^{-1} day^{-1}.

TABLE 4. Illustrative crop areas for the lunar farm.

Crop	Productivity of edible mass* g m^{-2} day^{-1}	Diet A Required edible production g person^{-1} day^{-1}	Diet A Growing area per person m^2	Diet A Growing area for 12 people m^2	Diet B Required edible production g person^{-1} day^{-1}	Diet B Growing area per person m^2	Diet B Growing area for 12 people m^2
Lettuce	60	10	0.2	2.4	10	0.2	2.4
Potato	27	229.2	8.5	102.0	272.3	10.1	121.2
Soybean	11	408.2	37.1	445.2	303.4	27.6	331.2
Wheat	30	114.7	3.8	45.6	158.3	5.3	63.6
Total		762.1	49.6	595.2	744.0	43.2	518.4

*Productivities are illustrative only, not maximum for each crop. Wheat, for example, has been grown as high as 60 g m^{-2} day^{-1}, but the value of 30 is used here so higher illumination could be used as a control to allow for higher production under unusual circumstances. It will be assumed that the other crops are similar in having higher productivities in conditions still to be investigated.
†Note this amount of soybeans creates a wasteful excess of edible protein (see Table 3).

maxima are not yet known. For another, the production rates during normal operations will be less that the maxima to allow the system to be controlled when storage reservoirs need to be readjusted. The productivities used here are representative of hydroponic crop yields that could be accomplished with today's technology.

As apparent in Table 4, using all the preceding calculations with attendant assumptions, most of the area of a lunar farm will be dedicated to soybeans (75% for diet A, 64% for diet B). This is a direct result of using soybeans to match the lipid requirements.

CONCLUSIONS

We have shown that a simple, generic crop model can represent the growth of four different candidate crops for Controlled Ecological Life Support Systems, providing mass fluxes associated with growth for any whole-system CELSS model. An initial simplicity is desirable because the model will tend to quickly become more complex when it incorporates additional refinements, particularly sensitivities to environmental variables. There is every reason to expect that a generic model like the one demonstrated here will be useful in constructing a new model system for studying the dynamics of a space farm.

An important problem exists in attempting to combine the four crops of lettuce, potatoes, soybeans, and wheat into an adequate diet. Besides being bland, there will be a serious overproduction of protein. Either diets with much lower lipid content than those shown must be designed and approved, or other crops with a higher lipid-to-protein ratio should be included. Rapeseed, for example, is about 50% lipid and about 20% protein; peanuts can be grown with as high as 54% lipid and as low as 21% protein (C. Mitchell, personal communication, 1988). If these crops were used to satisfy the lipid requirements, protein excess could be avoided. Unfortunately, little is known about the behavior of these crops in high production hydroponics. We recommend systematic crop growth experiments aimed at a balanced diet with minimal waste.

REFERENCES

Bugbee B. G. and Salisbury F. B. (1988) Exploring the limits of crop productivity I. Photosynthetic efficiency of wheat in high irradiance environments. *Plant Physiol.*, *88*, 869-878.

Gates D. M. (1980) *Biophysical Ecology.* Springer-Verlag, New York. 611 pp.

Krause M. V. and Mahan L. K. (1980) *Food Nutrition and Diet Therapy: A Textbook of Nutritional Care,* 7th edition. W. B. Saunders, Philadelphia. 525 pp.

Mitchell C. A., Knight S. L., and Fort T. L. (1986) Optimization of controlled environments for hydroponic production of leaf lettuce for human life support in space. In *NASA-TM-88215,* pp. 499-521.

Ride S. K. (1987) *Leadership and America's Future in Space: A Report to the Administrator.* U.S. Govt. Printing Office, Washington, DC. 63 pp.

Roberts L. (1988) Diet and health in China. *Science, 240,* 27.

Rummel J. D. and Volk T. (1987) A modular BLSS simulation model. *Adv. Space Res., 7,* (4)49-(4)67.

Volk T. and Rummel J. D. (1987) Mass balances for a biological life support system simulation model. *Adv. Space Res., 7,* (4)141-(4)148.

Wheeler R. M. and Tibbitts T. W. (1987) Utilization of potatoes for life support systems in space: III. Productivity at successive harvest dates under 12-h and 24-h photoperiods. *Am. Potato J., 64,* 311-320.

LONG-TERM LUNAR STATIONS: SOME ECOLOGICAL CONSIDERATIONS

N93-13995

Bassett Maguire Jr. and Kelly W. Scott

Department of Zoology
The University of Texas at Austin
Austin TX 78712

A major factor for long-term success of a lunar station is the ability to keep an agroecosystem functioning at a desirable, stable steady state with ecological stability and reliability. Design for a long-lived extraterrestrial manned station must take into account interactions among its subsystems to insure that overall functionality is enhanced (or at least not compromised). Physical isolation of food production, human living areas, recycling, and other systems may be straightforward; however, microbiological isolation will be very difficult. While it is possible to eliminate plant-associated microbiological communities by growing the plants aseptically, it is not practical to keep plants germ-free on a large scale if humans are working with them. Ecological theory strongly suggests that some kinds of communities or organisms effectively increase the stability of ecosystems and will protect the plants from potential pathogens. A carefully designed and maintained (lunar-derived) soil can provide a variety of habitats for effective microbial buffers while adding structure to the agroecosystem. A soil can also increase ecosystem reliability through buffering otherwise large element and compound fluctuations (of nutrients, wastes, etc.) as well as buffering temperature level and atmosphere composition. We are doing experiments in ecological dynamics and attempting to extend the relevant theories.

INTRODUCTION

The primary consideration of this paper is to outline some of the ecological design and management problems and possibilities of isolated human-containing, human-supporting agroecosystems, frequently referred to as Closed Ecological Life Support Systems (CELSS). Of the many possible topics within this category, those discussed here will be (1) problems related to the need of plant pathogen avoidance along with the necessary association between food-supporting plants and their unavoidably "dirty" human gardeners; (2) some possible stability problems stemming from possible internal dynamics of the human-plant agroecosystem; (3) a simple model of human nutritional requirements (except for substances, such as vitamin B_{12}, which are not produced by green plants) with appropriate portions of foods from the "recommended" CELSS food plant list, along with estimates of some of the requirements of the plants necessary for the production of the required amounts of the needed foods (including recommendation of animal use for food and companionship); and (4) a suggestion that somewhat more attention be given to the interacting needs and requirements of the components of (long-term) extraterrestrial station (ETS) support systems. In addition, brief descriptions of our preliminary and our current closed systems will be given.

PLANT-MICROBIAL INTERACTIONS

A major, but completely unavoidable problem is that human beings carry many species of microorganisms with them. Only about 10% of the approximately 10^{14} cells that we each carry around are really ours. The other 90% of these cells are of our "associates"; most of them are bacteria (*Savage*, 1977). Some of these microorganisms provide us with needed materials. For example, vitamin K, important in blood clotting, is normally provided to humans by some of their intestinal "associates." In any event, we cannot, in any practical way, produce trained, germ-free adult humans. (Imagine raising germ-free people from birth and then giving them adequate astronaut training while keeping them *completely* isolated microbiologically from the rest of the nonsterilized world.) In addition, extended experience on Earth shows that it will be extremely difficult to prevent those human-supporting agricultural plants in isolated agroecosystems from being exposed to people-carried microorganisms. We do not know what effects such microorganisms might have on otherwise germ-free plants.

The general method that no doubt will be used to avoid the introduction of plant pathogens into the system will be to eliminate plant-accompanying viruses and microorganisms (and other pests) from the agricultural plants by growing their progenitors axenically (in the absence of other species, including microorganisms). Elimination of pathogenic viruses will be more complicated than suggested by this simple prescription, but it can be done by use of already known techniques.

It is well known that plants naturally produce rich organic substrates around their roots and on the surfaces of their leaves and stems. For example, up to about 25% of the total carbon that the plant makes available to its roots may be lost from the plant by a combined excretion of low molecular weight organic molecules and loss of dead cells from the roots (*Barber and Martin*, 1976; *Newman*, 1978; *Burr and Ceasar*, 1984). Accumulations of rich and abundant microbial food material produced by the growth of the initially germ-free agricultural plants in an ETS would be rapidly invaded by microorganisms within the station. To the degree that the assortment of microorganisms within this system is restricted to species that are carried there by even well-washed humans, the invaders of the plant root zones (rhizospheres) and leaf surfaces (phylloplanes) will be of species that normally are associates of humans. Experience suggests that exclusion of all other (nonhuman associating) microbial species may also be difficult.

We do not have information concerning what effect these "unnatural" rhizosphere and phylloplane microorganisms might have on the plants. At best they will cause no difficulties. At worst, some of them will invade some of the plants and cause damage that will result in a reduction (perhaps catastrophic) of food yield. That some human-carried microorganisms will fall into the destructive category is strongly suggested by *Lasko and Starr* (1970), *Cooper-Smith and von Graeveniz* (1978), and *Starr* (1979). (See *Maguire*, 1980, for a more detailed discussion). *Lasko and Starr* (1970) inoculated plants with 45 different strains of the enterobacterium *Erwinia*, which had been isolated from various animals. Upon testing these by exposing plants to them, it appeared that 16 were harmless, 13 produced slight deleterious effects, and 16 damaged the plants as much as did strains of *Erwinia* that are considered to be serious plant pathogens. *Cooper-Smith and von Graeveniz* (1978) were concerned with cases of humans who were infected by a bacterium that later turned out to be *Erwinia herbicola*, previously recognized to be a plant pathogen. *Starr* (1979) summed up the situation by pointing out that some 200 species of bacteria and fungi were then known that attack and harm both plants and animals.

To counter this potential problem, as well as to help in the solution to several other problems that will be discussed below, we recommend that carefully selected and "purified" soil microbial communities be used. They should be inoculated onto the previously germ-free plants supplied to the ETS for food production. These "domesticated" microbial communities will use (and destroy) the organic materials released and cast off by the plants. They will be important in preventing other possibly damaging microorganisms from joining the plant-microbial community. These microbes also could be very beneficial in recycling sewage (kept free of heavy metals and toxic chemicals) that might be used to enrich the agricultural soils.

The theoretical reason that this strategy is expected to work is that plant pathogens have evolved a series of specializations that enable them to achieve contact with a host, penetrate that host in spite of the host's defences, and then to utilize the host as a resource on which to grow and reproduce. Because no organism can evolve to be maximally efficient in carrying out a large number of different kinds of tasks, what this means to plant pathogens is that they are generally inferior to many of the normal rhizosphere microorganisms in utilizing the exudates of roots and the roots' dead cells (such as hair cells and root cap cells) for their growth and reproduction. The normal rhizosphere organisms therefore tend to form a barrier, an important part of which is a zone of severe nutrient depletion around the plant roots that the pathogens must reach to be successful. The pathogens find this zone difficult to penetrate. However, with an absence (or low population level) of these normal rhizosphere microorganisms, which are specialized to use these organic root products, pathogens have much less difficulty in invading their host plants. In many instances, for reasons of these dynamics, the addition of populations of some kinds of soil or rhizosphere bacteria decreases the number of plants that are attacked by a pathogen (and also may decrease the severity of the symptoms in those plants that do come down with the disease). (See *Maguire*, 1980, for many references pertinent to the above.)

Considerable experimentation has been carried out in which various nonpathogenic microorganisms have been added to the rhizospheres of plants in frequently successful attempts to reinforce the normal rhizosphere microbiological community and better protect the plants from some of their important pathogens. Results have been sufficiently successful that some commercial application of such biological control of pathogens has developed. A number of biocontrol agents have been used. Among them are the bacteria *Pseudomonas sp*, *Pseudomonas fluorescens*, *Agrobacterium rhizogenes* (strain 84), *Bacillus mycoides*, *Bacillus pumilus*, and *Enterobacter cloacae*, as well as the fungi *Coniothyrium minitans*, *Gliocladium roseum*, and a number of species of *Trichoderma*. *Lynch* (1987) provides an excellent (although brief) review of the current state of this art.

The naturally developing rhizosphere communities of different plant species (and even of different varieties of one species) are different. As one of many possible examples, the peanut (*Arachis hypogaea* L.) varieties "Virginia" and "Spanish" and even different subvarieties within these varieties had different numbers of total bacteria and of *Azotobacter*, in their rhizosphere microbial communities (*Joshi et al.*, 1987). Total number of bacteria in the rhizosphere also was positively correlated with the yield of the individual plants.

Various individual species of rhizosphere microbial communities also appear to stimulate the growth of the plants. Also, in addition to the direct plant-protective function of some microbial species, the presence of some other species results in an elevation of the numbers of living bacteria in the rhizospheres of plants. In another example, *Secilia and Bagyaraj* (1987) added cultures of species within four genera of vesicular-arbuscular (VA) mycorrhizae to pot cultures of Guinea Grass (*Panicum maximum*). They recorded considerable increase in the number of bacteria and nitrogen fixers in the rhizosphere communities to which one of these three species was added. Presence of the fourth VA species did not correlate with change in the number of bacteria or nitrogen fixers, but it did correlate significantly with the number of Actinomycetes present (one, but not the other two VA species also produced this pattern of increase of Actinomycetes). Finally, in their very brief comment on the nonantipathogen effects of rhizosphere microbial communities on plant growth, *Vancura and Jandera* (1986) report on the production of plant growth hormones (kinetins, gibberillins, indole-3-acetic acid, and so on) by some rhizosphere microbial species. These growth hormones may have considerable effect on plant growth and yield. It is clear that there is much work yet to be done on the systems briefly illustrated by these examples. Development of research in these directions might make important differences in the kinds of agroecosystems that will be most useful on the Moon and other ETSs, as efficiencies and rates of food production may be greatly elevated by proper choices.

Some of the products of the rhizosphere community include volatile chemicals (such as ethylene, which may act as a plant hormone under some conditions) that will need to be removed from the atmosphere of ETSs. If human-carried microorganisms invade the rhizospheres of the plants, they also could result in problem volatiles. As one small example, *Belay et al.* (1988) have isolated methanogenic bacteria from human dental plaque. If these methanogens (or those that inhabit the intestinal tracts of about one-third of the adults of the U.S.) should be present and have the opportunity to be too active in ETSs, there might also be the problem of having to remove this gas from the atmosphere.

Finally, for this portion of the paper, there is the problem of the relatively ready movement of genetic elements among many of the microorganisms that share some environment. This kind of movement is known to provide bacterial species with abilities that they previously did not have. It is what has provided our hospitals, for example, with strains of infective bacteria that are

resistant to a number of different kinds of antibiotics (which is why infections that one acquires in a hospital may be especially nasty and difficult to cure). *Davey and Reanny* (1980) present a "genetic network" in which they illustrate the known paths of phage and plasmid transfer of genetic elements among 21 genera of bacteria. Represented in this web are 2 genera from the rhizoplane, 11 from the rhizosphere, 3 from bulk soil, 9 from "soil feces," and 1 from a human gastrointestinal tract (with 1 genus being found in—and counted in—2 of these habitats). *Reanny et al.* (1983) reinforce the suggestion that genetic elements pass rapidly among many genera of bacteria within natural systems, and discuss the evolutionary implications of the patterns observed. Transfer of genetic components (including nuclei) is also well known in the fungi.

What the above sections tell us is that microbial communities cannot be avoided if agroecosystems are to be used. If we wish to establish ETSs on the Moon or elsewhere we need a great increase in our understanding of these communities if we are to avoid complex and potentially serious ecological problems. Some of these have been briefly considered above. It seems clear that we need to learn how to design microbial communities, and need to know which, out of a very large number of possible designs, will be most effective in helping us to avoid really serious agroecological problems (at the same time it would be nice to have microbial systems that would enhance agricultural yield and perhaps do other useful things for the ETS). We must do a great amount of ecological research if we wish to use agroecosystems for feeding the people in ETSs; the alternative is to continue to bring sandwiches from Earth, which is not a viable economic proposition in the long run, especially as the ETSs get to be farther and farther from Earth. We have a long way to go, and need to get started in a number of research directions.

Plants of ETSs on the Moon and other planetary bodies may well be grown in carefully designed and cared-for soils because (1) soil cation exchange capacities provide effective buffers for many plant nutrients (an alternative to fail-safe hydroponic control systems); (2) soils provide temperature buffers for the plant roots; (3) soils provide a variety of habitats for beneficial soil microorganisms that could help to recycle sewage, and to destroy some kinds of toxic chemicals, in addition to protecting "their" plants; (4) soil provides support for plant roots and the plants themselves; (5) soil physical and chemical heterogeneity results in substantial increase in the range of chemical conditions that occurs among microhabitats reachable by plant roots and thereby possibly increasing the availability of nutrients needed by the plants (*Brady,* 1984); and (6) soils (of appropriate structure) on bodies that have planetary mass (such as the Moon) will be under the influence of gravity, which will cause them to drain under proper conditions. (Capillary forces within a soil, in the presence of no more than microgravity in nonspinning orbiting space stations, would prevent drainage of that soil. This is a very important factor in the consideration of use of soils in such nonspinning, orbiting stations.) Where there is adequate gravity, the use of soils requires less in the way of mechanics and control than do hydroponics, may provide other important benefits, and also may permit the people to spend less time in taking care of the plants.

STABILITY

There is controversy concerning ecological stability theory. We believe that *appropriate* communities of organisms (including communities made up of agricultural plants and "their" microorganisms) may be of considerable effect in increasing the stability of agroecosystems. Such systems may change less as a result of a given shock or perturbation than do simpler systems. In addition, these communities can return to approximately the preperturbation state more rapidly than others. (These properties are called, respectively, resistance and resilience by ecologists.) We are currently doing experiments to learn more about these ecological dynamics and to extend ecological theory concerning them.

The often-observed decrease in the number of kinds of microorganisms carried by people isolated from others for long periods of time is an indication of the lack of internal stability in the human-carried microbial community. This pattern has been observed in long expeditions to the Arctic and Antarctic, for example, where the incidence of communicable disease (flu and colds, for example) drops markedly after a while because there are no more susceptible people for the disease to be passed to and the disease dies out. This also happens with respect to microorganisms that appear not to induce immune reactions in the host. For example, *Taylor* (1974) points out that on longer space missions there is a reduction of the "normal" human-carried microbiota. It is as a result of this reduction, Taylor reasonably hypothesizes, that the potentially pathogenic yeast *Candida albicans* becomes more common as a result of the absence of some of its normal competitors. What these observations tell us is that the "normal" human microbial communities are not stable in and of themselves, and that in these isolated groups of humans, extinction of some microbial species is common. On Earth, the number of species in human-held microbial communities results in part from a continued reinvasion of each community by microorganisms from other humans (and from the environment in general). A number of these invaders are, at the time of invasion, new to the community. This also suggests that premission microbiological isolation, to reduce the amount of reinvasion (and the number of species carried), might be an important part of the preflight preparation of those leaving Earth to occupy ETSs, including those on the Moon.

Complex, steady-state communities of microorganisms are probably not to be expected (they are probably uncommon in natural ecosystems on Earth). Interaction among the processes of population growth, competition, and predation in complex biological systems probably at least sometimes makes for a system in which the dynamics, at least in detail, are fundamentally unpredictable (chaotic, in the formal, mathematical sense; see *Thompson and Stewart,* 1986, for a good, general introduction to chaotic dynamics). We predict that some of the dynamics, in both human-carried and plant-associated microbial communities, will turn out to have chaotic elements (see *Maguire,* 1978, for a model of a simple ecological community that becomes chaotic in both time and space). There are trends and patterns that are quite predictable even within the chaos of these ecological systems; the observed reduction of numbers of species in the microbial communities of small groups of isolated individuals is an example. Much more work on this and other aspects of the dynamics of these systems is needed.

HUMAN-SUPPORTING AGRICULTURE

One of us (*Maguire,* 1984) has published a very simple minimal model of a human-supporting agroecosystem. In this, some necessary quantitative and qualitative characteristics of the food produced by the crop plants suggested for CELSSs were examined. A mix of food from these plants was chosen such that the known

nutritional requirements of humans (except for vitamin B_{12} which is not produced by plants) would be met, while at the same time the amount of space required to grow the food would be kept low. Dietary needs considered by the computer nutritional program were calories, proteins (including amino acid content), fats, carbohydrates, vitamins, minerals, and trace minerals. From this analysis, a list was produced giving one possible set of average per-person daily amounts and kinds of food required. Only species on the current list of CELSS-acceptable crop plants were used (see Table 1). Also, as can be seen from this analysis, about 70 m^2 (and at least near optimum culture conditions) are needed to grow adequate amounts of each plant in this selection to provide a nearly adequate diet (it contains everything needed except for the vitamin B_{12}, also known as cobalamine) for one person. Transpiration of the agricultural plants required to produce this per capita kind and amount of food will be about 190 l of water per day. The per capita flows of some of the major components of

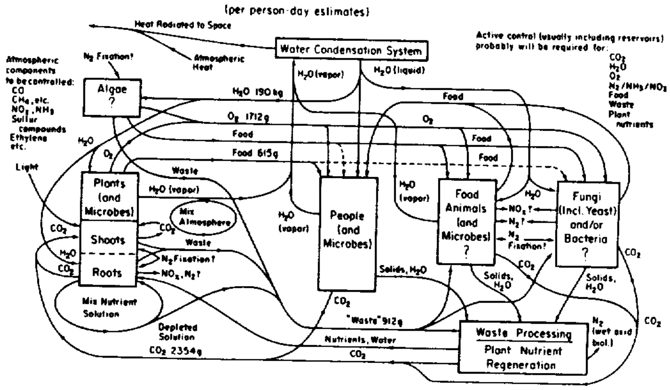


Fig. 1. Major material flows for extraterrestrial stations based on per-person daily requirements.

this human-supporting agroecosystem are illustrated in Fig. 1; these give an approximation of the magnitude of some of the required dynamics (and resultant machinery/management requirements).

As can be seen in Table 1, there are secondary and tertiary lists that were added to the list of primary CELSS-recommended plant list. Rabbits were included as they (1) do not eat the same food as humans and would use parts of the agricultural plants that are indigestible to humans (and therefore do not directly add to the cost as far as ecological or food chain energetics are concerned), (2) provide a good source of the otherwise problem vitamin, B_{12}, (3) provide for an important increase in the tastiness and satiation value of food produced by the agroecosystem, and (4) make satisfactory pets (provide companionship, can be "litter box" trained, like to be petted, etc.). Living in an ETS for extended periods is going to be difficult, and some small but important "luxury" items such as rabbits and roses appear to us to be well worth their costs. Onions, strawberries, and roses also are added to the proposed plant list, as tomatoes recently have been, because they (or other plant species to serve the same functions) can add considerable to life quality while adding little in the way of costs. Those who have been on long, isolated expeditions (as one of us has) well know the very great value of small amenities such as those we suggest.

CURRENT WORK

One of us (Maguire) developed, constructed, and successfully tested a preliminary closed system with which to ask some of the ecological questions posed above. Figure 2 is a photograph of part of this pilot system showing a variety of plants that (except for the red beets) were healthy and growing 20 days after the closure of the two experimental systems. Figure 3 gives the fluctuation of carbon dioxide over two 24-hour periods. It shows that there was substantial uptake of carbon dioxide during the daylight

TABLE 1. Per-person daily food values, production, and requirements (cooked where appropriate) for extraterrestrial stations (see text).

Food	Amount	g(dry)	kcal	g carb.	g protein	g fat	g/day/m^2 (edible)	agri: m^2/crew	agri:kg H_2O/day/crew	nonedible (g/day)
Rice (brn)	1 cup	58	232	50.0	4.9	1.2	8.4	6.9	18.9	87
Wheat (brn, fl)	1 cup	106	400	85.0	16.0	2.4	16.4	6.5	17.8	159
Potato (white)	1 large	50	145	32.8	4.0	0.2	19.0	2.6	6.5*	13
Potato (sweet)	1	53	161	37.0	2.4	0.6	30.0	1.8	4.9*	14
Soybean	1 cup	52	234	19.4	19.8	10.3	6.8	7.6	26.6*	121
Peanut	1 cup	142	842	27.2	37.4	71.6	8.9	16.0	48.0*	331
Sugar (beet)	0.5 cup	108	410	106.0	0.0	0.0	32.4	3.3	6.6*	132
Broccoli	3 spears	8	24	4.2	2.7	0.3	1.3	6.1	16.7	19
Peas (green)	0.5 cup	14	54	9.4	4.1	0.2	1.7	8.3	22.7	33
Lettuce	1 cup	3	7	1.6	0.5	0.1	13.6	0.2	0.2	1
Strawberry	1 cup	15	55	13.0	1.0	0.7	2.1	7.1	15.8	—
Onion	0.5 cup	6	22	5.0	0.9	0.1	3.1	1.9	5.2	2
Total		615	2586	390.6	93.7	87.7	X = 12.0	68.3	189.9	912
Tomato	1 medium	9	27	5.8	1.4	0.2	11.3	0.8	—	—
Yeast (baker's)	1 package	5	15	2.0	2.2	0.1	—	—	—	—
Alfalfa	per m^2	16	—	—	2.6	—	16.0†	—	—	—
Milk (goat)	1 cup	32	168	11.0	8.7	10.1	—	—	—	—
Lamb	3 oz	32	158	—	24.4	6.0	—	—	—	—
Rabbit	3 oz	34	184	—	24.7	8.5	—	—	—	—

* Those species for which water use data are given by *Tibbits and Alford* (1982), and which were used to produce the average of 2.74 kg/water/m^2/day used to estimate water use of the other species (see text).

† Edible for goats, rabbits, termites, etc., not humans (although human-digestible leaf protein of good quality and quantity can be extracted from alfalfa).

hours, and substantial return of carbon dioxide to the atmosphere during the night by the respiration of the plants and microorganisms within these closed systems.

Figures 4 and 5 illustrate the current version that we have designed and assembled and which is in preliminary stages of experimentation. As can be seen in the photographs, the wheat is healthy in this completely closed system. The slightly spindly nature of the plants is the result of somewhat low light levels along with lack of thigmomorphogenesis (a thickening of plant

Fig. 2. Plants in a Closed Ecological Life Support System chamber 20 days after closure. Geranium, chrysanthemum, rye, turnip, and clover were healthy and growing, but the red beets were doing poorly.

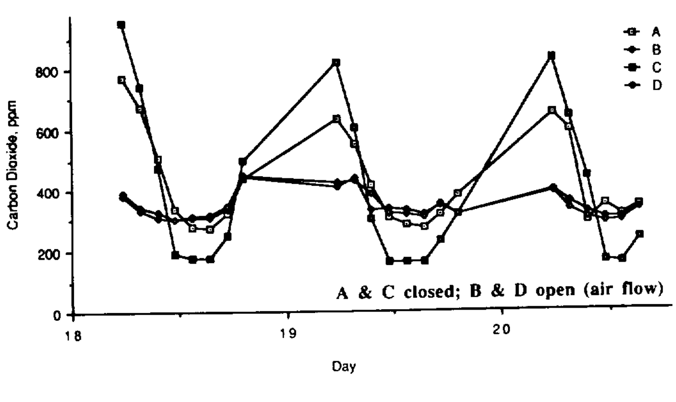


Fig. 3. The fluctuation of carbon dioxide in the chamber shown in Fig. 2 for the days 18 through 20 after closure.

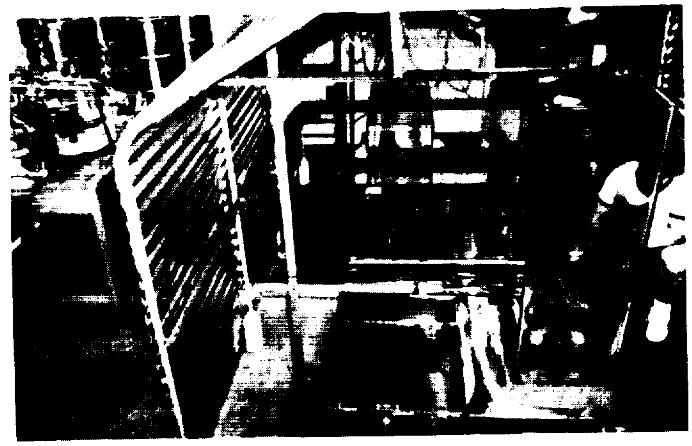


Fig. 4. Closed chambers of the current model, some containing 15-day-old wheat. Gas and water handling barrels, pumps, carboys, and tubing are at the upper left.

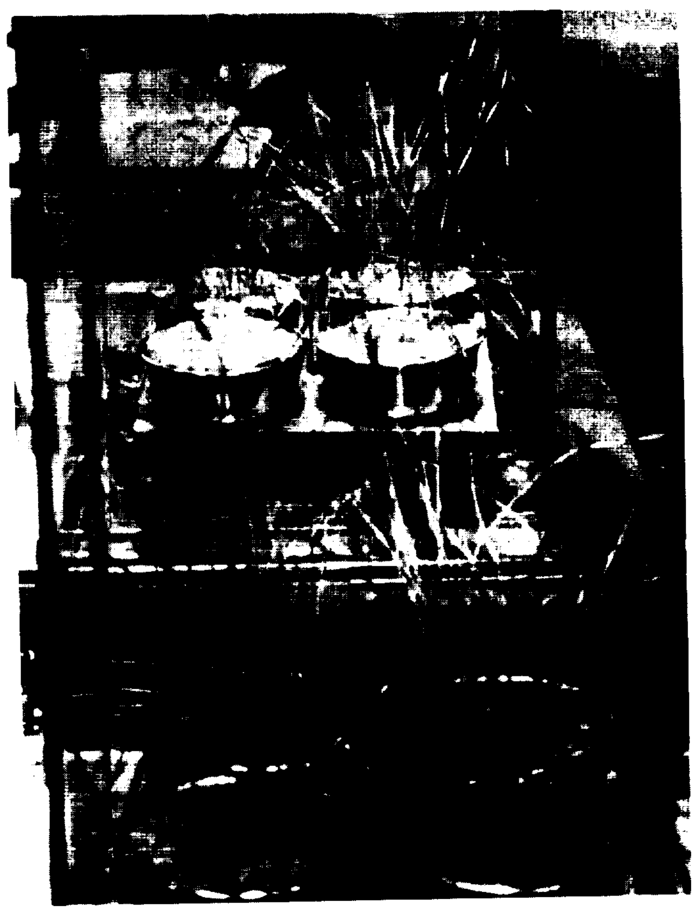


Fig. 5. Current model closed chamber containing 15-day-old wheat. See text.

stems induced by their bending, and normally caused by winds blowing on the plant out in the wider world). After a little more testing of these closed systems, we will use them to examine the resistance and resilience of wheat growth rate to calibrated perturbations in the absence of and in the presence of microbial communities of various kinds and complexities.

As a final note, we suggest that careful consideration be given to placing ETSs on the Moon at or near to the poles so it will be possible to continuously take advantage of sunlight by use of solar cells and power lines. Even better, if possible, would be to use light-weight mirrors, perhaps in association with other technologies, to direct light to the agricultural plants continuously (rather than just during the lunar day). Because the Moon lacks an atmosphere, this could be done reliably and easily over considerable distances. Efficiencies of use of light reflected by mirrors would be considerably larger than efficiencies of converting sunlight to electricity and then back to light again. In addition, the appropriate use of "cold" mirrors (mirrors that reflect visible wavelengths of light, but do not reflect the infrared of the solar spectrum) could considerably reduce the amount of heat that the station would have to dissipate to space. Of course, some infrared (far red) is necessary to adequately stimulate some physiological processes, including flowering, in various of the agricultural plants.

A FINAL SUGGESTION

As our last suggestion, we hope to see the establishment of a truly wide-ranging committee (including both NASA and non-NASA dependent people) that would estimate as well as possible the various interactions that could occur between the major ETS subsystems. With this information, then it should be possible to modify features of some subsystems without seriously affecting their performance, but such that important negative effects on other subsystems are reduced (and possible positive effects are increased).

It is also important that options not be closed too soon. Considerable development is still occurring in our understanding of many of the subsystems that will be important to "self supporting" lunar (or other) bases. It may well turn out that *total* system optimization will require that some of the subsystems be considerably different from (and more difficult to build and manage than) those currently under consideration.

SUMMARY AND CONCLUSIONS

It is our conclusion that there are considerable problems to be solved with respect to use of agricultural plants for human support (food and oxygen) in ETSs, such as bases on the Moon. Nevertheless, use of standard agricultural plants to provide food for the people seems to be the most reasonable (these plants have been chosen and bred for their usefulness and efficiency of food production over large stretches of space and time). Plant pathogen exclusion from ETSs appears to be best achieved by rendering the agricultural plants germ-free and then supplying them with carefully developed microbial communities that will protect them from the microorganisms unavoidably carried to the ETSs by their human occupants. Questions of stability of the human-supporting agroecosystem also need to be examined, and ways found to reduce the possibility of serious deleterious changes in the internal ecological dynamics within this ecosystem. Much research in these directions remains to be done (it has not even been really started). It is time for effective, long-term support of research to this end to be started, as it will take considerable time and effort to obtain the badly needed answers.

Acknowledgments. Support for some of this work by the Savannah River Laboratory, Aiken, S.C., is gratefully acknowledged.

REFERENCES

Barber D. A. and Martin J. K. (1976) The release of organic substances by cereal roots in soil. *New Phytol., 76,* 69-80.

Belay N., Johnson R., Rajagopal B. S., de Macario E. C., and Daniels L. (1988) Methanogenic bacteria from human dental plaque. *Appl. Environ. Microbiol., 54,* 600-603.

Brady N. C. (1984) *Nature and Properties of Soils,* 9th edition. McMillan, New York. 750 pp.

Burr T. J. and Caesar A. (1984) Beneficial plant bacteria. *CRC Crit. Rev. Plant Sci., 2,* 1-20.

Cooper-Smith M. E. and von Graevenitz A. (1978) Non-epidemic *Erwinia herbicola (Enterobacter agglomerans)* in blood cultures: Bacteriological analysis of fifteen cases. *Curr. Microbiol., 1,* 29-32.

Davey R. B. and Reanny D. C. (1980) Extrachromosomal genetic elements and the adaptive evolution of bacteria. In *Evolutionary Biology* (M. K. Hecht, W. C. Steare, and B. Wallace, eds.), pp. 113-147. Plenum, New York.

Joshi P. K., Kulkarni J. H., Chauhan S., and Sojitra V. K. (1987) A comparison of rhizosphere microflora in two varietal forms of groundnuts (*Arachis hypogaea* L.). *Zentralbl. Mikrobiol., 142,* 515-519.

Lakso J. U. and Starr M. P. (1970.) Comparative injuriousness to plants of *Erwinia spp.* and other enterobacteria from plants and animals. *J. Appl. Bacteriol., 33,* 692-707.

Lynch J. M. (1987) Biological control within microbial communities of the rhizosphere. In *Ecology of Microbial Communities* (M. Fletcher, T. R G. Gray, and J. G. Jones, eds.), pp. 55-82. Cambridge, New York.

Maguire B. Jr. (1978) Modeling of ecological process and ecosystems with partial response structures: A review and a new paradigm for diagnosis of emergent ecosystem dynamics and patterns. In *Proc. 1st International Conference on the State of the Art in Ecological Modeling* (S. E. Jorgensen, ed.), pp. 59-126.

Maguire B. Jr. (1980) *Literature Review of Human Microbes' Interaction with Plants.* NASA Contractor Report 166330. 215 pp.

Maguire B. Jr. (1984) Ecological problems in extra-terrestrial life support systems. *Sci. Tech. Ser., Am. Astronaut. Soc., 59,* 373-390.

Newman E. I. (1978) Root microorganisms: Their significance in the ecosystem. *Biol. Rev., 53,* 511-554.

Reanny D. C., Gowland P. C., and Slater J. H. (1983) Genetic interactions among microbial communities. In *Microbes in their Natural Environments* (J. H. Slater, R. Whittenbury, and J. W. T. Wimpenny, eds.), pp. 377-421. Cambridge, New York.

Savage D. C. (1977) Microbial ecology of the gastrointestinal tract. *Annu. Rev. Microbiol., 31,* 107-133.

Secilia J. and Bagyaraj D. J. (1987) Bacteria and actinomycetes associated with pot cultures of vesicular-arbuscular mycorrhizas. *Can. J. Microbiol., 33,* 1069-1073.

Starr M. L. (1979) Plant associated bacteria as human pathogens: Disciplinal insularity, ambilateral harmfulness, epistemological primacy. *Ann. Intern. Med., 90,* 708-710.

Taylor G. R. (1974) Space microbiology. *Annu. Rev. Microbiol., 28,* 121-137.

Thompson J. M. T. and Stewart H. B. (1986) *Nonlinear Dynamics and Chaos.* Wiley, New York. 376 pp.

Tibbits T. W. and Alford E. K. (1982) *Controlled Ecological Life Support System: Use of Higher Plants.* NASA CP-2231.

Vancura V. and Jandera A. (1986) Formation of biologically active metabolites by rhizosphere microflora. In *Microbial Communities of the Soil* (V. Jensen, A. Kjoller, and L. H. Sorensen, eds.), pp. 73-87. Elsevier, London.

ENGINEERING VERIFICATION OF THE BIOMASS PRODUCTION CHAMBER

N93-13996

R. P. Prince, W. M. Knott III, and J. C. Sager

NASA Kennedy Space Center
Kennedy Space Center FL 32899

J. D. Jones

NASA Goddard Space Flight Center
Greenbelt MD 20771

The requirements for life support systems, both biological and physical-chemical, for long-term human attended space missions are under serious study throughout NASA. The J. F. Kennedy Space Center "breadboard" project has focused on biomass production using higher plants for atmospheric regeneration and food production in a special biomass production chamber. This chamber is designed to provide information on food crop growth rate, contaminants in the chamber that alter plant growth, requirements for atmospheric regeneration, carbon dioxide consumption, oxygen production, and water utilization. The shape and size, mass, and energy requirements in relation to the overall integrity of the biomass production chamber are under constant study.

INTRODUCTION

The need to regenerate cabin atmosphere and water has been recognized by *MacElroy and Bredt* (1984) and *Gitel'zon* (1977). Until recently physical-chemical processes have been considered the most appropriate candidates for processing the life support resources. The use of higher plants in the recycling system was reported by *Gitel'zon et al.* (1975) and they indicated a reasonable measure of success. Based on a number of NASA studies, *Sweet and Tremor* (1978) asked for suggestions on the design of a chamber for higher plants. Other unrelated work by *Reid et al.* (1977) outlined a control system suitable to manage a plant growth chamber over a wide range of environments.

The Controlled Ecological Life Support System (CELSS) program managed by the Life Sciences Division of the Office of Space Science and Applications of the National Aeronautics and Space Administration (NASA) is committed to developing a system that provides basic life support requirements such as food, potable water, and breathable atmosphere for space crews on long-term space missions or extraterrestrial habitations. This program draws upon every aspect of the scientific community for information needed to accomplish a working CELSS and includes the utilization of research data accumulated over the past 16 years by an active grants research effort conducted under the CELSS program. To accomplish this biomass production, biomass processing, food preparation, product storage, atmospheric regeneration, waste management, crew habitation, analytical, and engineering and control are all required components.

In 1986 the Kennedy Space Center (KSC) began the "breadboard" project, which focused on a special biomass production chamber (BPC). This chamber was designed to function in a sealed (i.e., having an atmospheric leak rate of under 10% per day operating with an internal pressure of 12 mm H_2O above atmospheric) state while growing food crops. It was also designed to permit water and atmospheric contaminants to be collected and analyzed while growing different food crops and combinations of food crops. Physical and biological data combined will permit improvements to be made in the BPC and a more deliberate design of future plant growth chambers.

The term "verification" implies conformity with a truth or accuracy of a fact. It also signals a test of a theory or an examination of conformity to a standard. To physically verify the BPC requires a knowledge of the surrounding atmosphere, operating requirements, and cultural practices. To verify the crop growth needed will require an elaborate set of biological parameters. Another verification will involve the physical-biological interface. This has to do with those pieces (mostly physical) required to maintain integrity of any biomass production that might be suitable for microgravity environment. Since this BPC is designated as part of a breadboard project, changes in its operational mode, physical appearance, performance requirements and surroundings can and will be made as necessary.

Standards exist for maintaining the atmospheric seal of a spacecraft in a microgravity environment for a given period of time. Standards for measuring physical environmental parameters required to grow higher plants were edited by *Tibbitts and Koszlowski* (1979). *Tibbitts* (1984) also edited the NCR101 North Central Region Growth Chamber Committee quality assurance report for higher plant research conducted in growth chambers. Measurements on which to base certain biomass growth rates, contaminant levels, analytical monitoring, computer control algorithms, etc. have not been defined clearly. This paper will examine some of these issues and deal with a few processes in detail. The area of options will be examined in view of timeframes and assurances.

BIOMASS GROWTH REQUIREMENTS

Higher plant growth is regulated by physical and biological parameters. It is projected as a multidimensioned growth response phenomenon in which interactions between more than one parameter occur as shown in Fig. 1. Scientists have been

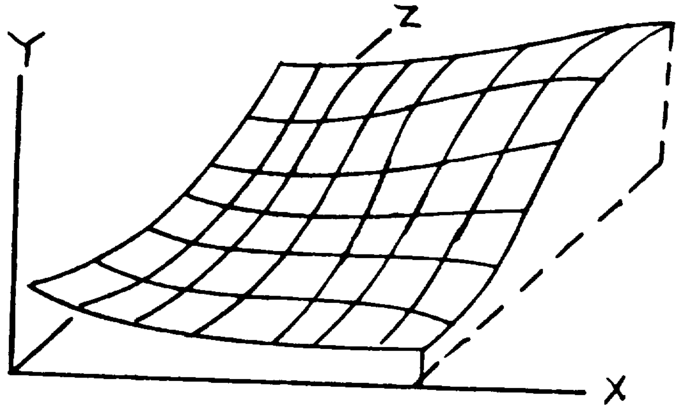


Fig. 1. A simplified view of a section of the nonuniform plant growth response surface.

investigating environmental parameters causing these growth responses. Some have endeavored to alter these environmental parameters to obtain higher energy transfer efficiencies, and have obtained success at finding the set of parameters to obtain high dry-matter yields of wheat (*Bugbee and Salisbury,* 1985, 1988). A better understanding of processes influencing this growth response is vital to the success of the CELSS effort.

The growth response surface may also be altered by mechanical or physical constraints such as the type of nutrient solution distribution systems, the plant support system, the volume needed in the root zone for root crops, the delivery systems used to supply oxygen to plant roots, etc. The use of an organic substrate tends to complicate nutrient delivery systems design from the standpoint of filtration and nutrient maintenance. The use of a nonabsorbing inorganic substance provides root anchor, increased volume, and added weight. An absorbing type of inorganic susbance also provides root anchor, increases system volume, adds weight, and complicates elemental balances within the nutrient system. For these reasons a thin-film continuous flow nutrient delivery system was designed for the KSC breadboard project.

This decision gave rise to whether a deep pool, thin-film, and continuous or intermittent flow would be the system of choice. A continuously flowing thin- (4-6-mm-deep) film type of nutrient delivery system was chosen since it might use less solution per plant, less total solution, and provide as good growth as other systems.

Nearly all the scientific data found in the literature were obtained without moving plants further apart as they grow to utilize radiation (light) more effectively and where an all-in-all-out planting-harvest scheme prevailed. Therefore, few scientific data are available for a given area where continuous cropping and plant spacing are practiced. Not all crops require spacing to maximize light utilization, but data on continuous cropping of a given area will be useful.

Table 1 gives the design requirements for the BPC. These requirements have been met in construction and now must withstand detailed evaluation. The monitoring and control ranges listed in Table 1 were considered adequate for the food crops being discussed for this ground-based test vessel. The crops are wheat, rice, soybean, bush beans, lettuce, sugar beets, sweet potatoes, white potatoes, peanuts, and tomatoes. We have grown

TABLE 1. Subsystem control and monitoring parameter requirements for the biomass production chamber (BPC).

Subsystem	Range for type
Heating, Ventilation, and Air Conditioning	
Controlled	
Air temperature	18-30°C
Relative humidity	60-70% RH
Ventilation rate	0.5-1 m sec^{-1}
Monitored	
Condensate water	400-500 l day^{-1}
Air filtration	99.9% at 0.3 μ
Gas and Pressure	
Controlled	
Oxygen	20.8%
Carbon dioxide	350-2500 μmol mol^{-1}
Chamber operating pressure	0.10-0.25 kPa
Radiation (Light)	
Controlled	
Radiation (light)	300-1000 μmol m^{-2} sec^{-1}
Photoperiod	0-24 hr
Nutrient Delivery	
Controlled	
Nutrient temperature	15-30°C
pH	5.5-6.5 pH
Conductivity	100-250 msm^{-1}
Flow rate	300 ml min^{-1} $tray^{-1}$

wheat, soybeans, bush beans, lettuce, and white potatoes to maturity in a commercial plant growth chamber using nutrient solution culture.

OTHER REQUIREMENTS FOR CROP GROWTH

Other factors that tend to influence plant response surfaces must be considered when evaluating the different components of a CELSS. Figure 2 shows a simplified way of looking at the different components. Within each component there may be many air, moisture, and people paths to control. Each must be evaluated and confirmed. Also, the components cannot function independently. For example, the system chosen for producing biomass will no doubt influence the waste management and biomass processing components. A much clearer picture can be drawn of the individual components and the total CELSS if many options are available.

While certain processes within the components of a CELSS may reach an ecological equilibirum, essentially every process, component, and the total CELSS will function on a real-time analytical analysis, process monitoring, and computer control system. Such control systems must be subject to the same verifications and options that prevail for other elements and components. Also there will exist a compromise, for the different activities may often conflict with biomass production. Further, it may be desirable to alter plant growth rate in order to accomplish certain outcomes.

VERIFICATION OF THE BPC

An existing steel vessel, 3.5 m in diameter by 7.5 m high, was modified to satisfy the previously mentioned BPC design requirements (Fig. 3). This modification consisted of installing 20 m^2 of shelf crop growing area on 4 levels for an area of

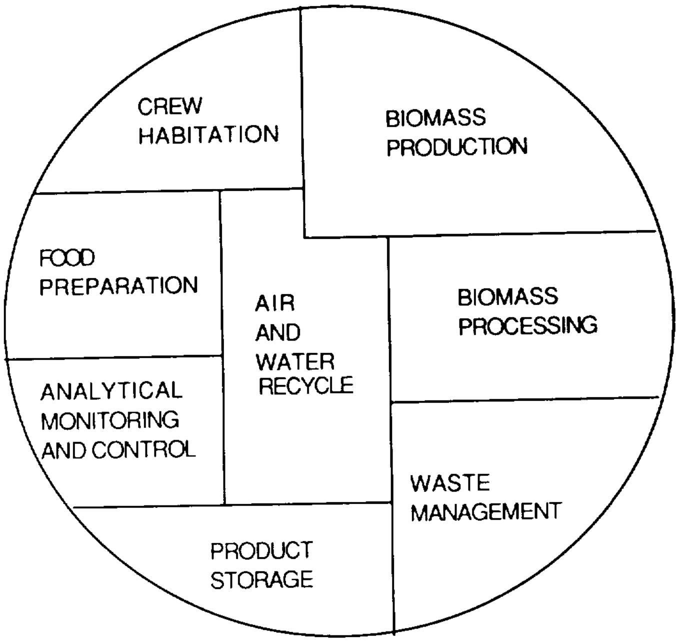


Fig. 2. A CELSS concept indicating air and water regeneration for all components and complete monitoring and computer control.

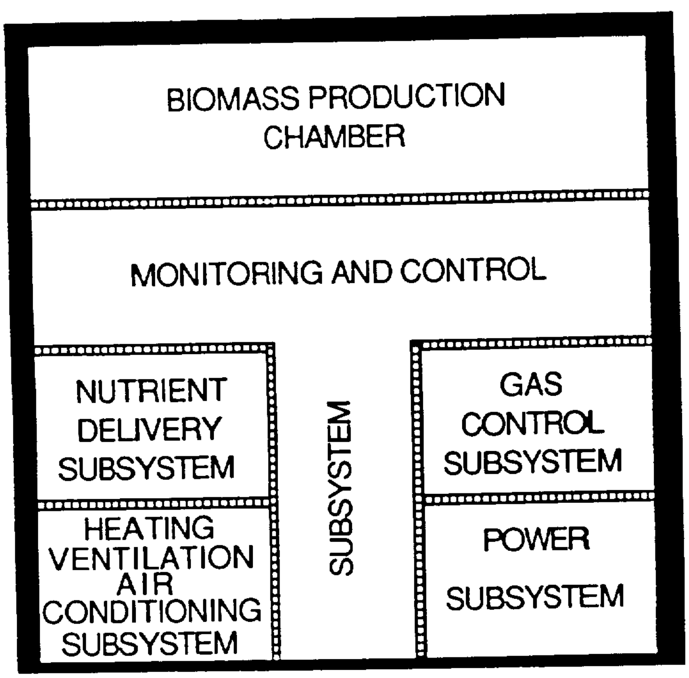


Fig. 3. Subsystem in place for maintaining and managing the biomass production chamber.

approximately 27 m^2 using 32 adjustable platforms. Above (approximately 1 m) each platform was mounted a lamp bank containing three 400-W high-pressure sodium (HPS) bulbs for a total of 96 bulbs. Eight lamp banks are located on each of the four growing levels. Two dimming controls are fitted to lamp banks on each level for a total of eight controls. Photosynthetic photon flux (PPF) can be computer controlled from 350 μmole m^{-2} sec^{-1} to 600 μmole m^{-2} sec^{-1} over the photosynthetic active radiation (PAR) waveband of 400 to 700 nm. All 96 lamp ballasts are located outside the chamber.

The stainless steel lamp banks were made with a Pyrex glass bottom and serve as a duct for air to pick up some lamp fixture heat as air returns to two air handling units. The time for one air cycle amounts to about 17 sec. Air enters the BPC beneath the lamp banks and above the plant canopy at a velocity of about 0.5 m sec^{-1}. During the air cycle temperature, relative humidity, and carbon dioxide are adjusted to preset levels. Oxygen (20.8%) and chamber pressure (12 mm H_2O above atmospheric) are maintained by releasing air or by the addition of breathing air. In addition to contaminant sampling inside the chamber, provisions were made in the duct system to sample supply and exhaust air.

An air handling unit (Fig. 4) consisting of a chilled water cooling coil, a hot water heating coil, a humidifier, an absolute filter, and a fan was in place for each of the two systems and served to direct the flow of air to and from the chamber. A 120-l stainless steel tank located beneath each cooling coil collected condensate water.

The nutrient delivery systems (Fig. 5) consisted of 64 isosceles-trapezoid-shaped plant growth trays, four 250-l nutrient reservoirs, plumbing, and fluid controls. Each tray contained its own plumbing and distribution header. The trays were constructed of polyvinyl chloride (PVC) and measured 25 mm deep by 432 mm wide at the wide end, by 178 m wide at the narrow end, by 0.84 m long, for an area of 0.25 m^2.

A tray top specifically designed for small grain consisted of a capillary plant support (CPS) larger than the one described by *Prince and Koontz* (1984) and is shown in Fig. 6. Approximately

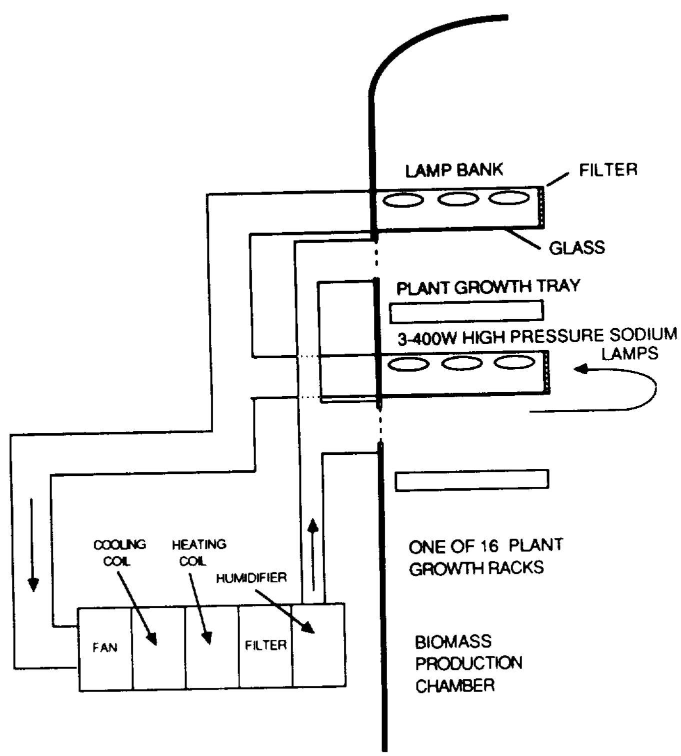


Fig. 4. Schematic of the heating, ventilating, and air conditioning subsystem.

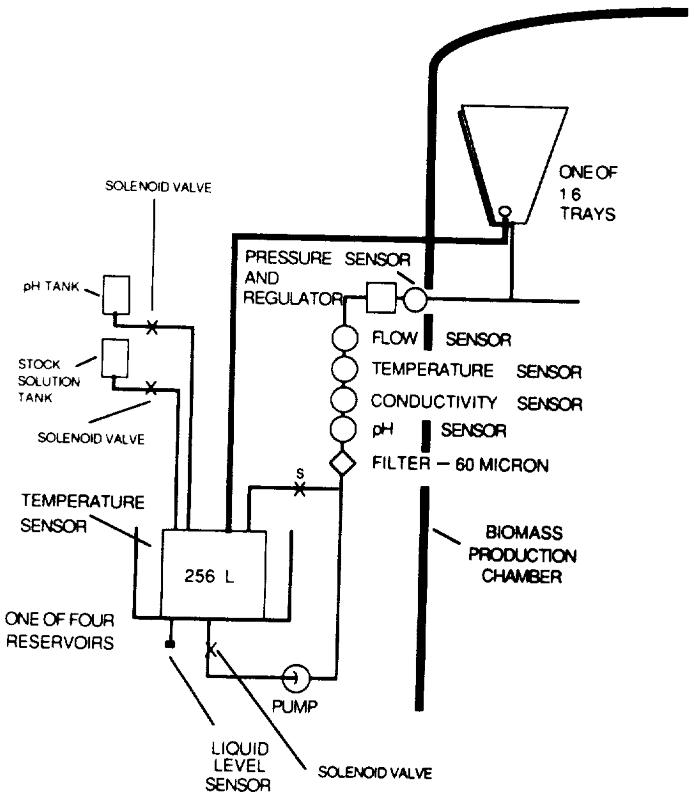


Fig. 5. Schematic of the nutrient delivery system.

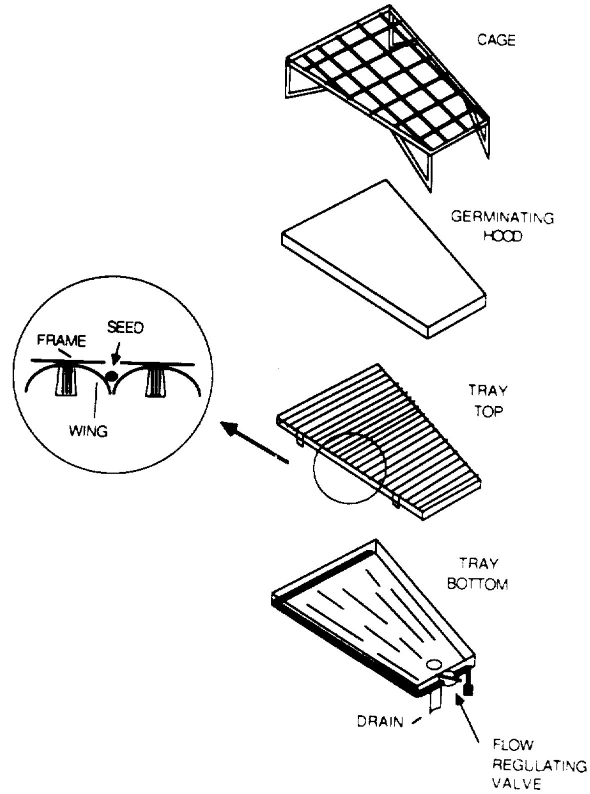


Fig. 6. Schematic of the capillary plant support (CPS) and the plant growth tray assembly.

TABLE 2. Physical and environmental parameters associated with biomass production chamber verification.

Physical		Environmental	
Parameter	Unit	Parameter	Unit
Ambient			
Total volume	m^3		
Leak rate	$l\ hr^{-1}$		
Positive pressure	mm H_2O		
Photosynthetic photon flux	μmole m^{-2} sec^{-1} (400-700 nm)	Relative humidity	%
		Day	
		Night	
Nonphotosynthetic shortwave radiation	700-2800 nm		
Longwave radiation	2800-100,000 nm	Partial pressure	Pa
Radiation source		Day	
Radiation filters		Night	
Barriers			
Lamp bank design		Carbon dioxide	μmol mol^{-1}
Photoperiod	hr	Day	
Temperature	°C	Night	
Day			
Night		Oxygen	%
		Day	
Air velocity through canopy	m sec^{-1}	Night	
Nutrient Solution			
Temperature	°C	Dissolved oxygen	%
Day		pH	
Night		Conductivity	ms m^{-1}
Condensate water	$l\ hr^{-1}$	Volume	m^3
Nutrient flow rate	$l\ sec^{-1}$ $tray^{-1}$	Mass	kg

5.6 m of linear distance was provided for seed placement per tray. Up to 400 wheat seeds were used for yield studies. Once the seeds were in place, the germinating hood was placed on the tray. This hood contained a plastic screen underneath the top for the purpose of holding free water that would be evaporated over time, thereby maintaining a high relative humidity on the seeds and young seedlings. Following a 48-hr germinating period the hood was removed and a cage to keep the wheat upright at maturity was installed.

A control system utilizing sensors, control valves, switches, and a programmable logic controller (PLC) was installed. The PLC was programmed to maintain the environmental, liquid, and gas parameters within specified limits. It also managed alarms and arranged to shut down certain subsystems in the event out-of-range limits were reached. A separate set of sensors was installed for the specified purpose of monitoring all the parameters associated with chamber control and many parameters having to do with the particular experiment. The dataset consisted of 5-min storages of averages taken over 1-min intervals.

Evaluation of the degree of seal with respect to time and the total enclosed volume was made using the gas control and monitoring systems. This specification was met, as were the atmospheric temperature and relative humidity conditions. The nutrient delivery systems required fewer specific controls but more monitoring sensors. For all subsystems the control performace of the BPC without plants exceeded design specifications (Table 2).

VERIFICATION OF BIOMASS GROWTH

Lawlor (1987) explains photosynthesis as "the process by which organisms convert the energy of light into the chemical energy of organic molecules." He explains this process in terms of light (400 to 700 nm) energy, carbon dioxide, temperature, nutrition, and water. The biomass growth phenomenon as discussed earlier in this paper interacts with the verification process. Each and every new set of environmental parameters controlled to produce a crop may be used to verify growth (Table 3). Unfortunately, the dataset accompanying much of the early literature relating to crop growth in plant growth chambers did not contain all of the dataset we now need.

Detailed crop growth requirements were not a part of the BPC environmental requirements. To grow a respectable crop in a reasonable period of time yielding a considerable amount of edible biomass with little trouble was a satisfactory goal. Specific inputs over given time periods using certain cultural practices in a controlled environment should result in a certain edible biomass yield according to the literature for specified crops. The impact of a sealed chamber atmosphere on crop growth was a relative unknown. In recent times, however, commercial chambers have become much higher in atmospheric seal, giving confidence that major problems will not be encountered.

Using information from the literature and trials conducted at KSC in commercial growth chambers, Table 3 was constructed to give a partial listing of parameters needed and tasks to be accomplished to verify biomass growth. By collecting such data and making broad comparisons with similar commercial growth chamber data, it should be possible to evaluate crop growth and production. In all cases the dataset must contain descriptive details of cultural practices, nutrient maintenance methods, and environmental changes that occurred.

TABLE 3. Biological parameters and measurements associated with verifying biomass production chamber parameters.

Parameter	Unit	Parameter	Unit
Crop		Cropping System	
Variety		All-in-all-out	
		Continuous	
Seed storage		Interval	
Time		Spacing	
Temperature	°C	Other†	
Moisture	% RH	Plant support‡	
Controlled			
Atmosphere			
Propagation*		Plant, Nutrition	
Seed		N	mm
Cell culture transplant		P	mm
		K	mm
		Ca	mm
		Mg	µm
		S	µm
		Fe	µm
		Mn	µm
		Zn	µm
		Cu	µm
		B	µm
		Mo	µm
		Cl	µm
Germination	%	Nutrient maintenance§	
Survival	%	Conductivity	
Plant density	Plants m^{-2}	On-line analysis	
Growth rate¶			
Height	mm	Volume**	m^3
Diameter	mm	Area††	m^2
Dry matter	g		
Photosynthetic rate¶	µmol m^{-2} sec^{-1}	Leaf area index††	
Harvest (dry weight)	g $plant^{-1}$		
Total biomass	gm^{-2}	Analysis - Biomass	
Edible biomass		Proximate	
Nonedible biomass		Chemical	
Shoot:shoot ratio			
Moisture content (wet weight)	%		

For the parameters indicated, an investigator must perform the following:
* A complete description of equipment needed and procedure used is required.
† Describe and depict the spacing system.
‡ Identify the complete plant holder, seed to harvest.
§ Describe in detail.
¶ Show graph with respect to time.
** Total plant volume, plants only.
†† Ratio of leaf area to the growing area, m m^{-1}.

It may be desirable to obtain a plant canopy as quickly as possible after planting for reasons of light utilization. For some crops this may be achieved by spacing the individual plants as they grow, thereby maintaining a somewhat uniform canopy. The cultural practice of spacing and moving was referred to by *Prince and Koontz* (1984) as "continuous production." In this procedure and where the scheduled time between harvesting and seeding is less than seven days, the term "crop growth rate" may be justified. In all cases the exact area and the days (seed to harvest), as well as the planting schedule, must be part of the dataset. Further, knowledge is lacking as to how to vary growth

rate in relation to oxygen demand and food needs. Such a system is important when considering limited oxygen storage, unplanned crew activity, and required waste management processes that may require oxygen. Utilization of carbon dioxide and water will also be changed. The influence of microbial activity, pathogens, and insects must become part of the verification process. Detection of changes in net photosynthesis and identification of cause will become important pieces of information for evaluation purposes.

SUMMARY

NASA KSC has designed and constructed a biomass production chamber as part of the breadboard project. It is 3.5 m in diameter by 7.5 m high, and the total biomass production area is 20 m^2 on four levels. A thin-film continuous-flow nutrient delivery system supplies water and nutrients to plant roots.

The chamber and the ability of plants to grow in the chamber are subject to verification. The chamber can be verified from a strict physical and environmental compliance standpoint. The flexibility in limits permitted must ultimately fall within the bounds of adequate biomass growth. Verification of biomass production is determined by dry matter for a particular set of environments and feedback algorithms.

REFERENCES

Bugbee B. G. and Salisbury F. B. (1985) Studies on maximum yield of wheat for the controlled environments of space. In *NASA TM-88215*, pp. 447-485.

Bugbee B. G. and Salisbury F. B. (1988) Exploring the limits of crop productivity. *Planet Physiol., 88,* 869-878.

Gitel'zon I. I. (1977) *Problems of Creating Biotechnical Systems of Human Life Support.* NASA TTF-17533. 272 pp.

Gitel'zon I. I., Kovrov B. G., Lisolvskiy G. M., Okladnikov Yu. N., Rerberg M. S., Sidko F. Ya., and Terskoy I. A. (1975) *Problems of Space Biology. Experimental Ecological Systems Including Man, Vol. 28.* NASA TTF-16993. 291 pp.

Lawlor D. W. (1987) *Photosynthesis: Metabolism, Control and Physiology.* Longman, New York. 262 pp.

MacElroy R. D. and Bredt J. (1984) Current concepts and future direction in CELSS. In *Life Support Systems in Space Travel*, pp. 1-9.

Prince R. P. and Koontz H. V. (1984) Lettuce production from a systems approach. In *Int. Soc. for Soilless Culture Proc.*, pp. 533-546. Wageningen, The Netherlands.

Reid W. S., Desjardens R. I., and Small E. (1977) A six chamber indiurnal plant micro-environment cabinet. *Trans. ASAE, 20,* 1061-1066.

Sweet H. C. and Tremor J. N. (1978) Plant growth chambers on Spacelab: A call for scientific input. *Am. J. Bot., 65,* 594-600.

Tibbitts T. W. (1984) Quality assurance procedures for accuracy in environmental monitoring—draft proposal. *Biotronics, 13,* 43-46.

Tibbitts T. W. and Kozlowski T. T., eds. (1979) *Controlled Environment Guidelines for Plant Research.* Academic, New York. 413 pp.

SCENARIOS FOR OPTIMIZING POTATO PRODUCTIVITY IN A LUNAR CELSS

N93-13997

R. M. Wheeler

NASA Biomedical Operations and Research
Kennedy Space Center FL 32899

R. C. Morrow, T. W. Tibbitts, and R. J. Bula

Wisconsin Center for Space Automation and Robotics
University of Wisconsin
Madison WI 53715

The use of controlled ecological life support systems (CELSS) in the development and growth of large-scale bases on the Moon will reduce the expense of supplying life support materials from Earth. Such systems would use plants to produce food and oxygen, remove carbon dioxide, and recycle water and minerals. In a lunar CELSS, several factors are likely to be limiting to plant productivity, including the availability of growing area, electrical power, and lamp/ballast weight for lighting systems. Several management scenarios are outlined in this discussion for the production of potatoes based on their response to irradiance, photoperiod, and carbon dioxide concentration. Management scenarios that use 12-hr photoperiods, high carbon dioxide concentrations, and movable lamp banks to alternately irradiate halves of the growing area appear to be the most efficient in terms of growing area, electrical power, and lamp weights. However, the optimal scenario will be dependent upon the relative "costs" of each factor.

INTRODUCTION

The establishment of bases on the surface of the Moon has been identified as one of the primary initiatives to be pursued by NASA (*Ride,* 1987). Potential economic benefits from mining the lunar surface may provide an additional impetus for establishing these bases (*Kulcinski,* 1988). As lunar outposts increase in size, the high cost of resupply from Earth will make it imperative to reduce the quantity of these resources. Controlled ecological life support systems (CELSS), systems that recycle chemical and biological resources necessary to support human life, will therefore come to play a crucial role in the long-term support of these bases (*Ride,* 1987).

Green plants (primarily various algae and higher plants) will play an integral part in a CELSS because the process of photosynthesis utilizes radiant energy (400-700 nm) to convert carbon dioxide and water into carbohydrates and oxygen. In addition to removing carbon dioxide from the atmosphere and producing food and oxygen, higher plants can purify water through the process of transpiration. The gravitational field of the Moon should be sufficient to allow the production of higher plants using systems that have been adapted from the technologies used for controlled-environment plant growth on Earth (*Bula et al.,* 1987).

Several species of higher plants have been selected for study as possible CELSS candidate crops (*Tibbitts and Alford,* 1982). One of these species is the white, or Irish potato (*Solanum tuberosum L.*). Potato exhibits several characteristics that are of value in a CELSS (*Tibbitts and Wheeler,* 1987), including high rates of productivity and a high ratio of edible to inedible biomass (high harvest index). In addition, they are a good quality food source (rich in carbohydrates with adequate protein levels), are easily stored for long periods, and can be prepared in a number of culinary forms. There is also a good information base available on potato culture, and a substantial amount of work has been done in recent years to investigate potato productivity and physiology under controlled environments. In general, high tuber yields (tubers being the edible underground portion of the potato) are promoted by short photoperiods (i.e., diurnal cycles with short days and long nights), moderate to high irradiance (1/4 to 1/2 full sunlight), cool temperatures (<20°C), and high carbon dioxide levels (e.g., 1000 ppm). Certain environmental requirements, however, can be offset or compensated for by altering other factors. For example, tubers will form without any dark periods (i.e., continuous irradiation) provided irradiance is sufficiently high and temperatures are cool (*Wheeler and Tibbitts,* 1987a; *Wheeler et al.,* 1986). Also, high carbon dioxide concentrations can partially substitute for high irradiance. When all factors are optimal, yields as high as 40 g m^{-2} day^{-1} of tuber dry matter have been obtained from controlled environments (*Tibbitts et al.,* 1989). This equates to over 200 metric tons (fresh weight) per hectare, or approximately seven times the average field yield in the United States.

In contrast to most traditional agronomic systems, the goal of maximum production per unit area may not be the major concern in a CELSS. Rather, the primary goal will likely be to optimize productivity based on the relative costs of various factors. Thus, it is important to assess various ways in which the growing environment of potatoes might be manipulated to optimize production in relation to the factors that are most likely to be limiting in a lunar CELSS. These include the growing area (or volume) available, electrical power (or possible total energy) availability, and launch weight of the hardware required to support plant growth. The weight of lighting equipment is of particular significance because the cost of transporting lamps for a 30-person CELSS to the lunar surface could run into hundreds

of millions of dollars (not including purchase price) at the conservatively estimated launch cost of $10,000 per kilogram (*Koelle*, 1988). Other factors that might be limiting to plant productivity include temperature and humidity control, water and nutrients to support plant growth, inert gases to maintain atmospheric pressure, and reliability and safety considerations.

BASELINE ASSUMPTIONS

To evaluate the tradeoffs between various CELSS environments in terms of growing area, energy efficiency, and initial payload weight, a "baseline" situation needs to be defined. The following assumptions will be made for the purpose of this discussion:

1. ***Potatoes will be the sole biomass producing crop.*** In reality, a true CELSS diet would consist of several different plant species, matched to provide a balanced and interesting diet (*Hoff et al.*, 1982). Eventually, various production scenarios will need to be developed that take into account the integration of the different species used for biomass production in a lunar CELSS.

2. ***Temperature and humidity control, water and nutrients, inert gases, and reliability and safety will be considered nonlimiting.*** More detailed concepts of an actual lunar CELSS are required before the impact of these factors can be evaluated.

3. ***The base will have 30 inhabitants.*** A lunar base with 30 inhabitants has been projected for the year 2010 (*Ride*, 1987). Because the caloric requirement for each inhabitant will be approximately 2800 kcal d^{-1} (*NAS*, 1980), the total needs of all the inhabitants would be on the order of 84,000 kcal d^{-1}. Potatoes provide 3.73 kcal g^{-1} of tuber dry weight (*Watt and Merril*, 1963), so 30 inhabitants would require about 22,5000 g (dry weight) of tubers per day, or about 112 kg (250 lb) of fresh tubers.

4. ***Electrical lamps will be used in a lunar CELSS.*** Although the possibility exists that direct solar radiation can be utilized for plant growth in a lunar CELSS, lamps will still be necessary to provide irradiance during the two-week-long lunar "nights." Currently, one of the most efficient irradiation sources for photosynthetic lighting is the 1000-W high-pressure sodium lamp (*Tibbitts*, 1987). The relationship between lamp input power and the photosynthetically active radiation (PAR) produced can be conservatively estimated at 1 W m^{-2} of lamp input power for each μmol sec^{-1} m^{-2} of PAR produced (The Phytofarm, DeKalb, IL, personal communication, 1987), which is approximately equivalent to a 20% conversion of electricity to PAR. The weight of a 1000-W high pressure sodium lamp (bulb, ballast, and reflector) has been estimated at 20 kg (W. W. Grainger, Inc., 1987 catalog).

5. ***Tuber productivity will follow trends shown in Fig. 1.*** Approximate tuber productivity values in response to various combinations of irradiance, photoperiod, and carbon dioxide level are shown in Fig. 1. These curves are derived from experimental data (*Wheeler and Tibbitts*, 1987a; R. M. Wheeler and T. W. Tibbitts, unpublished data, 1988), though productivity at high and low levels of irradiance are estimations based on related work and past experience.

MANAGEMENT SCENARIOS

Fixed Lamps, Low Carbon Dioxide Concentrations

The first set of scenarios involves a fixed lamp arrangement to provide irradiance at 400 and 800 μmol sec^{-1} m^{-2}, 12-hr and 24-hr photoperiods, and "Earth" ambient (350 ppm) or low carbon dioxide levels (Table 1). Those scenarios that utilize high irradiance levels (scenarios 1 and 2) require the least growing area to provide daily caloric requirements, but scenarios utilizing 12-hr photoperiods (scenarios 2 and 4) are most efficient in terms of energy required. Use of continuous, low-level irradiance (scenario 3) requires the least initial lamp weight. Although scenario 1 is the most efficient on an area basis, it is the least efficient on any energy basis and its lamp weight is high. This would be of use in situations where area is limited, but energy and lamp weight are of minimum concern. Scenarios 2 and 3 are equivalent in terms of area and energy efficiency, but the lamp weight for scenario 3 is half that for scenario 2. Scenario 3 would provide a good compromise if all three potentially limiting factors were of equal concern. Scenario 4 is most efficient in terms of energy and is moderate in terms of weight, but it requires a large growing area. This scenario would be useful if growing area were of minimum concern.

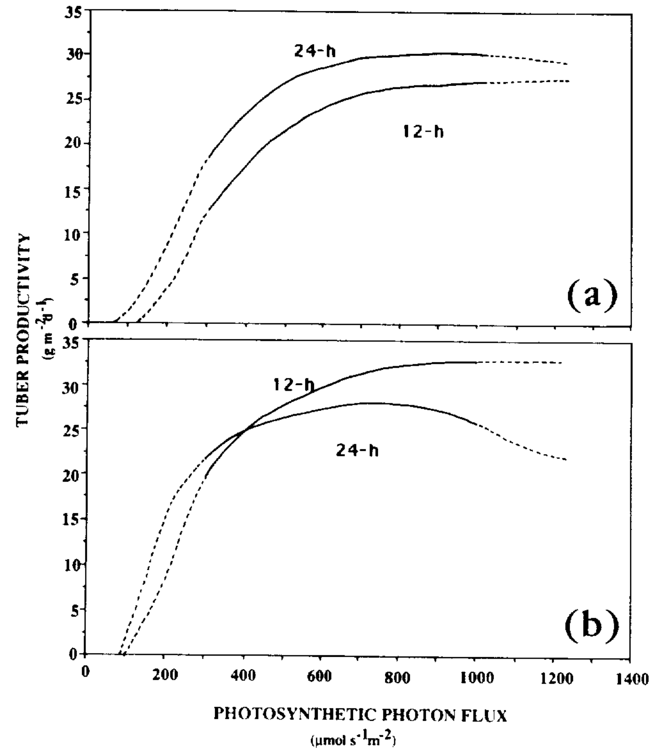


Fig. 1. Potato productivity curves for **(a)** low and **(b)** high carbon dioxide concentrations at various photosynthetic photon flux (irradiance) levels (*Wheeler and Tibbitts*, 1987a; R. M. Wheeler and T. W. Tibbitts, unpublished data, 1988). Productivities at high and low photosynthetic photon flux (broken lines) have been estimated based on related work.

Fixed Lamps, High Carbon Dioxide Concentrations

The next set of possible scenarios again assumes fixed lamps but is based on the use of carbon dioxide enrichment to increase the productivity of potato plants under the 12-hr photoperiods to levels nearly equivalent to those observed under the 24-hr photoperiods, essentially substituting for increased irradiance. However, increasing carbon dioxide concentrations has only a small effect on plants grown for 24 hr at 400 μmol sec^{-1} m^{-2}, and no effect on those grown at 800 μmol sec^{-1} m^{-2} (R. M. Wheeler and T. W. Tibbitts, unpublished data, 1988). Using carbon dioxide

enrichment, scenario 6 (Table 1) now becomes the most efficient on an area basis, while scenario 8 becomes the most efficient on an energy basis. In addition, carbon dioxide enrichment results in a substantial decrease in the number of lamps required for growing plants under a 12-hr photoperiod. With the use of carbon dioxide enrichment, 12-hr photoperiods show a definite advantage in productivity efficiency compared to the use of 24-hr photoperiods regardless of radiation level. If energy, growing area, and lamp weight were of equal concern, scenario 8 would be the best selection of the scenarios thus presented, including all carbon dioxide level scenarios.

Movable Lamp Arrangement

Because the potential cost of transporting lamps to the lunar surface is so great, it might be desirable to utilize movable lamp banks (*Wheeler and Tibbitts,* 1987b). By breaking the growing area into segments, half the segments could then be irradiated during the first 12-hr period (out of 24 hr) and the other half irradiated during the second 12-hr period. This reduces the number of lamps required by half while maintaining desired productivity levels (Tables 1 and 2, scenarios 10 vs. 4 and 12 vs. 8), and allows continuous use of available power. Alternatively, lamps could be positioned twice as densely to obtain irradiance (with a 12-hr photoperiod) twice that possible by lighting the entire area with the same number of lamps over a 24-hr photoperiod (Tables 1 and 2, scenarios 9 vs. 3 and 11 vs. 7). In fact, if mobility of the lamp bank is not in itself a limiting factor and carbon dioxide can be maintained at high concentrations, it would always be better to double lamp density (~doubling PAR) over half of the growing area (Table 3, column 2 vs. column 1). If area is not as limiting as power or lamps, it would again be better to use alternate 12-hr photoperiods (with movable lamps) but with twice the planted area (Table 3, column 3 vs. column 1). This would provide a productivity level equivalent to two 12-hr yields as compared to one 24-hr yield. If potatoes can be successfully grown under an 8-hr:16-hr light:dark cycle without serious reductions in productivity, three 8-hr photoperiods during each 24 hr might provide even greater increases in growing efficiency. It is noteworthy that if lamp and ballast weights could be reduced (e.g., through the development of small, energy efficient, solid state ballasts), the initial payload weight of lamps might be removed as a primary limiting factor in a lunar CELSS. However, the equipment required to make the lamp banks movable adds an unknown increment of weight that needs to be taken into consideration.

TABLE 1. Management scenarios for optimizing production of the 22,500 g day^{-1} of potato tubers required to satisfy caloric needs for 30 inhabitants in a lunar CELSS using an arrangement of fixed lamps.

Scenario	Irradiance	Photoperiod	Area Requirement	Energy Requirement	Area Efficiency*	Energy Efficiency	Lighting System Weight†
	(μmol sec^{-1}m^{-2})	(hr)	(m^2)	(kWhr d^{-1})	(g m^{-2} d^{-1})	(g kWhr^{-1})	(kg)
Low Carbon Dioxide Concentration (350 ppm)							
1	800	24	776	14,900	29	1.51	12,400
2	800	12	900	8,640	25	2.60	14,400
3	400	24	938	9,005	24	2.50	7,504
4	400	12	1184	5,683	19	3.96	9,472
High Carbon Dioxide Concentration (1000 ppm)							
5	800	24	776	14,900	29	1.51	12,400
6	800	12	726	6,970	31	3.23	11,616
7	400	24	900	8,640	25	2.61	7,200
8	400	12	882	4,234	25.5	5.31	7,056

*Also termed productivity. Adapted from *Wheeler and Tibbitts,* 1987a and Wheeler and Tibbitts, unpublished data, 1988. Values based on the average of 2 cultivars, Denali and Norland.

† Including ballast, bulb, and reflector.

TABLE 2. Management scenarios for optimizing production of the 22,500 g day^{-1} of potato tubers required to satisfy caloric needs for 30 inhabitants in a lunar CELSS using an arrangement of movable lamps.

Scenario	Irradiance	Photoperiod	Area Requirement	Energy Requirement	Area Efficiency*	Energy Efficiency	Lighting System Weight †
	(μmol sec^{-1}m^{-2})	(hr)	(m^2)	(kWhr d^{-1})	(g m^{-2} d^{-1})	(g kWhr^{-1})	(kg)
Low Carbon Dioxide Concentration (350 ppm)							
9	800	alt. 12‡	900	8640	25	2.60	7200
10	400	alt. 12	1184	5683	19	3.96	4736
High Carbon Dioxide Concentrations (1000 ppm)							
11	800	alt. 12	726	6970	31	3.23	5808
12	400	alt. 12	882	4234	25.5	5.31	3528

*Also termed productivity. Adapted from *Wheeler and Tibbitts,* 1987a; and Wheeler and Tibbitts, unpublished data, 1988. Values based on the average of 2 cultivars, Denali and Norland.

† Including ballast, bulb, and reflector.

‡ Alternate 12-hr photoperiods—half the growing area irradiated during the first 12-hr period, half irradiated during the second 12-hr period.

TABLE 3. Comparisons of fixed and movable lamp configurations based on an equal energy input.

Fixed lamp configuration		Movable lamp configurations			
1		2		3	
1 × area*		1 × area†		2 × area‡	
Irradiance	Yield	Irradiance	Yield	Irradiance	Yield
(μmol sec^{-1}m^{-2})	(g m^{-2}d^{-1})	(μmol sec^{-1}m^{-2})	(g m^{-2}d^{-1})	(μmol sec^{-1}m^{-2})	(g m^{-2}d^{-1})
300	18	600	26	2 × 300	30(2 × 15)
400	25	800	28	2 × 400	44(2 × 22)
500	27	1000	29	2 × 500	50(2 × 25)
600	28	1200	30	2 × 600	52(2 × 26)

*Lamps covering entire growing area (1 × density), 24-hr photoperiod.
† Lamps covering 1/2 of the growing area (2 × density). After a 12-hr photoperiod, lamps are moved to other 1/2 of growing area for another 12-hr photoperiod.
‡ Lamps covering 1/2 of the growing area (1 × density), except growing area is *doubled* in size. Therefore, lamps are spaced identically to those in column 1, but are alternated between each half of the growing area as for column 2.

Yield data are averaged over high and low carbon dioxide concentrations and for two potato cultivars, Denali and Norland (*Wheeler and Tibbitts,* 1987a; Wheeler and Tibbitts, unpublished data, 1988).

Other Scenarios

The management scenarios above, while simplified for the purpose of discussion, provide a framework within which additional scenarios can be generated by the manipulation of various factors and then evaluated and compared. For example, some of the lamps used could be placed within the plant canopy to improve the efficiency of irradiation absorption by the plants. This might result in an increase in productivity without a corresponding increase in required power inputs. Another possibility would be to utilize the growing area more efficiently (i.e., reduce the amount of open space between plants during early growth). This could be done by using a variable spacing mechanism, but the complexity of such a system might negate any increase in area-use efficiency obtained. An alternative would be to use an intercropping management system. At the per plant spacing used to determine productivity factors in this discussion (0.2 m^2), potatoes do not form a closed canopy until five to six weeks after planting (*Tibbitts and Wheeler,* 1987). A short season crop, such as lettuce, could be planted in the culture unit between the young potato plants and harvested before the canopy closes. Again, this would increase productivity of the CELSS with minimal additional input.

CONCLUSION

The crop management scenario that is ultimately chosen for a lunar CELSS will depend upon the factor or factors that are most limiting in terms of cost. A lunar base will likely evolve and assume several configurations depending on the stage of development of the base. Therefore, biomass production in the CELSS will be a dynamic process, changing with prevailing base configurations to optimize productivity. For example, as a lunar base expands, the area available for plant growth may become less limiting, thereby favoring those management scenarios that are energy efficient at the expense of area efficiency. However, the increase in growing area might result in factors such as carbon dioxide or lamp weight becoming limiting. Likewise, development of an energy intensive industrial process (i.e., lunar oxygen processing) might require cutbacks in the power available to the plant growing unit. Such a situation would favor a mangement scenario that is very energy efficient.

In any CELSS, maximum crop yield probably will not be the main objective. Rather, obtaining efficient production based on system limitations will be the primary concern. The management scenarios discussed represent an attempt to address crop production in a lunar CELSS from a limiting factor perspective. More detailed evaluation of these and other factors will be needed in order to determine break-even points between development of a CELSS and resupply of life support requirements from Earth. Similar system analyses for all potentially useful CELSS crops will enable the integration of these crops into an overall management program for the lunar CELSS.

REFERENCES

Bula R. J., Corey R. B., Volkweiss S. J., and Tibbitts T. W. (1987) *Concepts for a Commercial Space-based Plant Growth Unit.* WCSAR Tech. Rpt., AR2-8704-1, Madison. 6 pp.

Hoff J. E., Howe J. M., and Mitchell C. A. (1982) *Nutritional and Cultural Aspects of Plant Species Selected for a Controlled Ecological Life Support System.* NASA CR-166324, NASA Ames Research Center, Moffett Field. 125 pp.

Koelle H. H. (1992) The influence of lunar propellant production on the cost-effectiveness of cis-lunar transportation systems. In *The Second Conference on Lunar Bases and Space Activities of the 21st Century,* this volume.

Kulcinski G. L. (1988) Commercial attractiveness of D-He3 fusion reactors. *UWFDM-55,* Univ. of Wisconsin, Madison. 49 pp.

National Academy of Sciences (1980) *Recommended Dietary Allowances,* 9th edition. Natl. Acad. Sci.—Natl. Res. Coun. Publ. No. 2941, Washington, DC. 185 pp.

Ride S. K. (1987) *Leadership and America's Future in Space. A Report to the Administrator.* U.S. Govt. Printing Office, Washington, DC. 63 pp.

Tibbitts T. W. (1987) Greenhouse lighting systems: An overview. In *Proc. Natl. Plug Prod. Conf.* (N. H. Agnew, ed.), pp. 61-69. Iowa State University Research Foundation, Inc., Ames.

Tibbitts T. W. and Alford D. K., eds. (1982) *Controlled Ecological Life Support System—Use of Higher Plants.* NASA CP-2231, NASA Ames Research Center, Moffett Field. 84 pp.

Tibbitts T. W. and Wheeler R. M. (1987) Utilization of potatoes in bioregenerative life support systems. *Adv. Space Res., 7,* 115-122.

Tibbitts T. W., Bennett S. M., Morrow R. C., and Bula R. J. (1989) Utilization of white potatoes in CELSS. *Adv. Space Res., 9,* 53-59.

Watt B. K. and Merril A. L. (1963) *Composition of Foods.* USDA-ARS Agric. Handbook No. 8, Washington, DC. 147 pp.

Wheeler R. M. and Tibbitts T. W. (1987a) Utilization of potatoes for life support systems in space: III. Productivity at successive harvest dates under 12-h and 24-h photoperiods. *Am. Potato J., 64,* 311-320.

Wheeler R. M. and Tibbitts T. W. (1987b) Productivity and cost tradeoffs of various environments for growing potatoes in a CELSS. In *Space Life Sciences Symposium: Three Decades of Life Science Research in Space,* pp. 26-27. NASA, Washington, DC.

Wheeler R. M., Steffen K. L., Tibbitts T. W., and Palta J. P. (1986) Utilization of potatoes for life support systems. II. The effects of temperature under 24-h and 12-h photoperiods. *Am. Potato J., 63,* 639-647.

POTENTIAL OF DERIVED LUNAR VOLATILES FOR LIFE SUPPORT

R. J. Bula, L. J. Wittenberg, T. W. Tibbitts, and G. L. Kulcinski

University of Wisconsin
Madison WI 53706

The lunar regolith contains small quantities of solar wind implanted volatile compounds that have vital, basic uses for maintaining life support systems of lunar or space settlements. Recent proposals to utilize the helium-3 isotope (He-3) derived from the lunar regolith as a fuel for fusion reactors would result in the availability of large quantities of other lunar volatile compounds. The quantities obtained would provide the annual life support replacement requirements of 1150 to 23,000 inhabitants per tonne of He-3 recovered, depending on the volatile compound. Utilization of the lunar volatile compounds for life support depends on the costs, in terms of materials and energy, associated with their extraction from the lunar regolith as compared to the delivery costs of these compounds from Earth resources. Considering today's conservative estimated transportation costs ($10,000 per kilogram) and regolith mining costs ($5 per tonne), the life support replacement requirements could be more economically supplied by recovering the lunar volatile compounds than transporting these materials from Earth resources, even before He-3 will be utilized as a fusion fuel. In addition, availability of lunar volatile compounds could have a significant cost impact on maintaining the life support systems of the space station and a Mars base.

INTRODUCTION

Efforts toward settlements on the Moon and Mars will require major technological developments in the area of life support. Two recent reports concerning future U.S. space efforts (*Paine et al.*, 1986; *Ride*, 1987) point out that the key to living and working in space is the development of reliable life support systems that are not dependent on Earth resources. A bioregenerative life support system that closes the food, water, and air loops has the potential of providing the human requirements for survival in a space environment independent of Earth resources.

The lunar regolith contains small quantities of volatile compounds implanted from the solar winds. These volatile compounds have vital, basic uses for establishing life support systems of lunar or space bases by providing (1) raw materials for food production and food processing and (2) an atmosphere in the space base structures (Fig. 1). The available carbon, as carbon dioxide, hydrogen, nitrogen, and water of the lunar volatile compounds can be combined with small amounts of other materials derived from the lunar regolith to produce food through photosynthesis and autotrophic hydrogen and nitrogen bacteria.

The cost effectiveness for using these lunar volatile compounds in a life support system has been greatly enhanced by the recent proposal to use the helium-3 isotope (He-3) derived from the lunar regolith as a fuel for fusion reactors (*Wittenberg et al.*, 1986). *Li and Wittenberg* (1991) have developed a model of He-3 mining using a relatively low heating temperature of 700°C and have calculated the amounts of volatiles that would be produced from the regolith at that temperature (Table 1). Thus, large quantitites of other lunar volatile compounds would be evolved during procurement of the He-3 (Fig. 2). The number of inhabitants supported for a year by the nitrogen, water, and carbon dioxide derived with each tonne of He-3 mined is shown in Fig. 3.

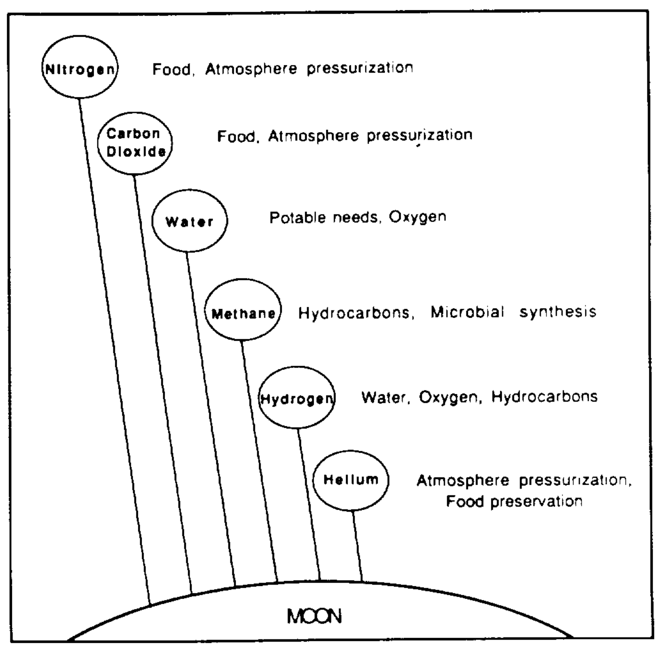


Fig. 1. Potential applications of solar wind deposited lunar volatile compounds for life support.

NITROGEN REQUIREMENT

The nitrogen derived from the lunar volatile compounds can be converted by appropriate bacteria to ammonia and then incorporated into proteins and other food materials. In addition, nitrogen will serve a very necessary role by providing the principal gas required for maintaining atmospheric pressures in the living and working areas of the lunar base and for the plant growing

TABLE 1. Estimated amounts of lunar volatile compounds released from lunar regolith heated to 700°C, volatile compound replacement requirements, and amount of regolith processing required to provide the requirements.

Volatile Compound	Amount Evolved* from Regolith (g per tonne)	Per Inhabitant: Volatile Requirements (g per day)	Per Inhabitant: Required Regolith Processing (tonnes per day)
Nitrogen	4.0	960	240
Carbon dioxide	12.0	210	18
Water	23.0	390	17
Oxygen†	-	410	-
Methane‡	11.0	-	-
Hydrogen§	43.0	-	-
Helium¶	22.0	-	-

*From *Li and Wittenberg* (1991).

†Will be derived from electrolysis of water derived with the lunar volatiles or from reduction of lunar ilmenite.

‡Can be used as substrate for microbial synthesis of more complex carbon-containing compounds.

§Can be used to reduce ilmenite to produce water or oxygen.

¶No life support need exists, but may be used to replace a portion of the nitrogen required to maintain atmospheric pressure.

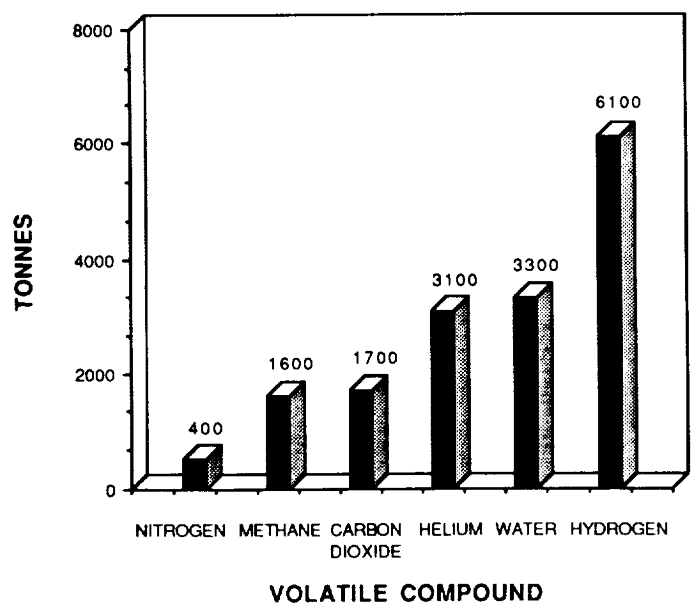


Fig. 2. Tonnes of lunar volatile compounds per tonne of He-3 recovered from the lunar regolith.

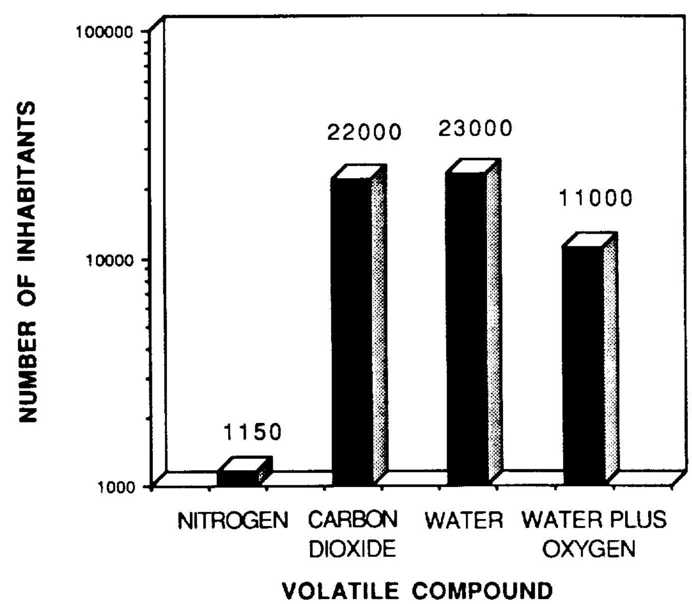


Fig. 3. Number of inhabitants supported for a year by the nitrogen, carbon dioxide, and water derived with each tonne of He-3 mined.

facilities. The requirements for initially pressurizing the space base volumes are not large, but the requirements for atmospheric pressure maintenance of these volumes would be substantial because of atmospheric leakage from the lunar structures and ingress and egress activities. The amount of nitrogen required to maintain atmospheric pressure represents over 99% of the annual nitrogen replacement requirement because only a small amount would be lost in the food production, food processing, and waste recycling operations of the life support system, even if a 10% annual loss is assumed.

The annual replacement requirement of nitrogen is based on providing a volume of 100 m^3 of living and working space per person and the volume associated with a bioregenerative life support system. If a 1.0% per day leakage rate is assumed for this volume, and an atmospheric pressure of 101 kPa is maintained, the annual per person replacement requirement of nitrogen would be 350 kg (0.96 kg per day × 365 days).

It is estimated that 400 tonnes of nitrogen will be recovered with each tonne of He-3 recovered from the regolith. This amount of nitrogen would provide the annual nitrogen replacement requirement of 1150 people. The quantities of helium recovered from the lunar regolith could be used as a partial substitution for the nitrogen in the atmosphere. This would extend the supply of nitrogen in proportion to the percentage of helium substitution possible. Research is needed to determine what percentage of nitrogen in the atmosphere can be replaced with helium.

OXYGEN REQUIREMENT

Oxygen is a critically important requirement of a life support system. Gaseous oxygen has not been found among the lunar volatile compounds; however, heating the lunar regolith to 700°C, as proposed for the extraction of He-3, does result in a portion of the hydrogen reducing the iron-oxide-bearing regolith materials to form water. The oxygen required for life support could be derived by electrolysis of the water obtained in this manner. An alternative method of obtaining the needed oxygen is by hydrogen reduction of lunar-surface ilmenite and electrolysis of the water as proposed by *Gibson and Knudsen* (1985). The primary use of oxygen produced by this or similar methods would be as a propellant. Thus, the amount involved for life support purposes would be relatively inconsequential by comparison.

Replacement requirements of oxygen are associated with atmospheric leakage and loss in the food production, food processing, and waste recycling operations. If the partial pressure of oxygen in the atmosphere is maintained at a level equivalent to the Earth's atmosphere (20.2 kPa) for the volumes described for the nitrogen requirements, the annual oxygen replacement would be 95 kg per person per year (0.26 kg per day × 365 days).

The amount of oxygen lost in the other aspects of the life support system can be estimated from data quantifying the amount of oxygen given off by plants. It is estimated that a 20-m^2 area of plants would provide the daily caloric requirements of one person (*Wheeler and Tibbitts,* 1987). A plant area of this size would give off approximately 1500 g of oxygen per day. If a 10% loss of this oxygen is assumed in the food production, food processing, and waste recycling operations, then 150 g of oxygen per person per day would need to be replaced. This amounts to an annual replacement requirement of 55 kg per person (0.15 kg per day × 365 days). Thus, considering the losses associated with atmospheric leakage and with the food and waste recycling processes, the total oxygen replacement requirement per person per year would amount to 150 kg.

CARBON DIOXIDE REQUIREMENT

Analysis of the annual carbon dioxide requirement is based on a 10% loss in the food production, food processing, and waste recycling operations because the carbon dioxide loss associated with atmospheric leakage is negligible. A 20-m^2 plant area produces approximately 2100 g of carbon dioxide per day (*Wheeler and Tibbitts,* 1987). If a 10% loss of carbon dioxide in the food production, food processing, and waste recycling operations is assumed, then 210 g per person per day would need to be replaced. This would amount to an annual carbon dioxide replacement requirement of 77 kg per person (0.21 kg per day × 365 days). It is estimated that approximately 1700 tonnes of carbon dioxide will be recovered with each tonne of He-3, thereby providing the annual estimated carbon dioxide replacement requirement of 22,000 people.

WATER REQUIREMENT

Water replacement requirements are based on estimates that a person requires approximately 3900 g of potable water per day (*NASA,* 1985). This does not represent the total water requirement, but rather only the amount of potable water for drinking, food preparation, and in unprepared food. If 10% of this water amount is lost during the recycling process, then 390 g of water per person per day would need to be replaced. This indicates an annual water requirement of 142 kg per person (0.39 kg per day × 365 days).

The total annual replacement amount of water can be calculated to include the loss associated with providing the potable water and the oxygen. It is estimated that approximately 3300 tonnes of water will be recovered with each tonne of He-3 recovered. If only the replacement requirement associated with the drinking water loss is considered, the 3300 tonnes of water would provide the annual estimated water replacement requirement of 23,000 people. If the water is used to provide the replacement for both the water and oxygen loss, the 3300 tonnes of water would provide the annual replacement requirement of approximately 11,000 people.

COSTS OF LUNAR-DERIVED VOLATILE COMPOUNDS COMPARED WITH DELIVERY COSTS OF RESUPPLIES FROM EARTH RESOURCES

Utilization of the lunar volatile compounds for life support will depend on costs, in terms of materials and energy, associated with their extraction from the lunar regolith as compared to the delivery costs of these compounds from Earth resources. The value of He-3 as a fusion fuel is estimated to be at least $1,000,000 per kilogram (*Kulcinski,* 1988). Obviously, if the lunar volatile compounds used for life support are obtained as a part of the He-3 extraction process, the costs of obtaining the non-He-3 volatile compounds on the Moon would be much less than the delivery costs from Earth resources.

Today's transportation costs of Earth resources to a lunar base are optimistically estimated to be $10,000 per kilogram (*Koelle,* 1991). Considering that the annual total life support material replacement (nitrogen, carbon dioxide, oxygen, and water) is estimated at 719 kg per person, the present-day transportation costs of these life support materials would approximate $7,190,000 per person per year. The number of lunar base inhabitants has been projected to be 30 by 2010 (*Ride,* 1987). Annual transportation costs, on the basis of today's cost estimates, for replacement of life support materials for a lunar base of that size would amount to $215,700,000. It is anticipated that future transportation costs may be reduced by an order of magnitude, or to $1000 per kilogram of payload transported from the Earth to the Moon.

By comparison, the costs of recovering the lunar volatile compounds from the lunar regolith can be estimated on the basis of the amount of regolith that would have to be mined to provide the life support replacement requirements. Large-scale regolith mining costs, such as would be involved in recovering large quantities of He-3, are estimated at $5 per tonne of regolith handled (*Sviatoslavsky and Jacobs,* 1988). Mining the regolith for the sole purpose of life support replacement materials would not be considered as large-scale mining and, therefore, the per tonne mining costs could be higher than $5. Comparisons of the break-even costs of lunar regolith mining compared to transportation costs from Earth to a lunar base are shown in Fig. 4. The relationships shown in Fig. 4 are based on the assumption that 240 tonnes of regolith per inhabitant per day must be mined and processed to supply the nitrogen replacement requirement (Table 1). Mining this amount of regolith will be sufficient to supply the replacement requirements of all the other volatile compounds. At

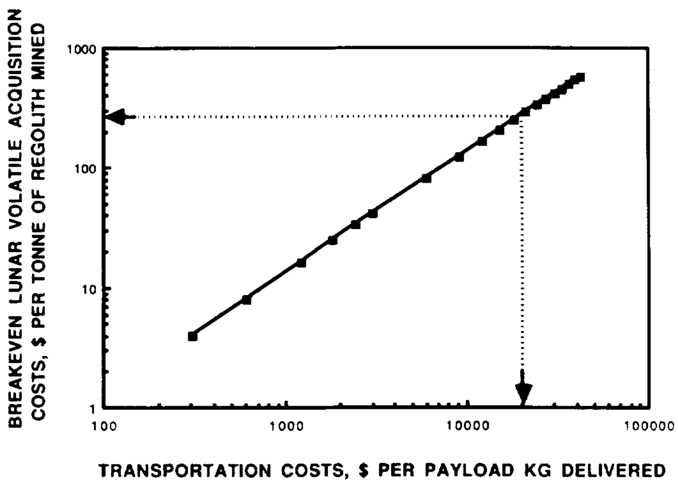


Fig. 4. Comparison of costs for supplying the life support replacement requirements from lunar regolith volatile compounds vs. transportation costs for resupply from Earth resources. The dotted lines correspond to twice the costs estimated by *Koelle* (1991).

transportation costs of $20,000 [twice the current costs estimated by *Koelle* (1991)], it would be more economical to obtain the life support replacement materials from the lunar regolith if mining costs were less than $200 per tonne. Likewise, if mining costs are less than $5 per tonne [as currently estimated by *Sviatoslavsky and Jacobs* (1988)], then transportation costs to the Moon would need to be less than $400 per kilogram to be economically competitive. These cost comparisons do not take into consideration the possibility of using helium for replacing a portion of the nitrogen used for maintaining atmospheric pressure. By using some of the available helium, the mining costs would be reduced because less regolith would need to be mined to obtain the replacement life support materials since considerably more helium than nitrogen is recovered per tonne of regolith (Table 1).

Availability of lunar volatile compounds would provide additional, distinct advantages related to life support for inhabitants of space bases. The quantities of replacement supplies available on the lunar surface would allow some relaxation of the otherwise stringent recycling requirements being projected for a space-based life support system. Some of the waste materials and other carbon-containing volatile compounds, such as methane, could be utilized by plants and microorganisms to produce complex carbon compounds. These complex carbonaceous compounds could serve as raw materials for the synthesis of other products required at a space station, such as plastics. Also, the lunar volatile compounds, or the synthesized products (food), could be exported to other space bases, such as the space station and Mars, more economically than from Earth resources. The value of the lunar volatile compounds in this context is not possible to estimate at this time; however, it is likely to be significant, particularly as the number of inhabitants at space bases increases.

It appears reasonable to conclude that the life support replacement requirements of a lunar base could be more economically supplied by recovering the lunar volatile compounds than transporting these materials from Earth resources even before He-3 will be utilized as a fusion fuel. Therefore, development of technology to recover lunar volatile compounds could be started in the next decade without waiting for the D-He-3 fusion reactors to be built on Earth. The early use of the lunar volatile compound recovery technology could reduce significantly the costs of maintaining the life support systems of the space station and of settlements on the Moon and Mars.

REFERENCES

Gibson M. A. and Knudsen C. W. (1985) Lunar oxygen production from ilmenite. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 543-550. Lunar and Planetary Institute, Houston.

Koelle H. H. (1992) The influence of lunar propellant production on the cost-effectiveness of cislunar transportation systems. In *The Second Conference on Lunar Bases and Space Activities of the 21st Century*, this volume.

Kulcinski G. L. (1988) *Commercial Attractiveness of D-He^3 Fusion Reactors*. UWFDM-755, Univ. of Wisconsin, Madison. 49 pp.

Li Y. T. and Wittenberg L. J. (1992) Lunar surface mining for automated acquisition of helium 3: Methods, processes, and equipment. In *The Second Conference on Lunar Bases and Space Activities of the 21st Century*, this volume.

NASA (1985) *Engineering and Configuration of Space Stations and Platforms*, pp. 468-473. Noyes Publications, Park Ridge, NJ.

Paine T. O. et al. (1986) *Pioneering the Space Frontier. The Report of the National Commission on Space*. Bantam, New York.

Ride S. K. (1987) *Leadership and America's Future in Space: A Report to the Administrator*. U.S. Govt. Printing Office, Washington, DC. 63 pp.

Sviatoslavsky I. N. and Jacobs M. (1988) Mobile helium-3 mining system and its benefits toward lunar base self-sufficiency. In *Space Engineering, Construction, and Operation in Space* (S. W. Johnson and J. P. Wetzel, eds.), pp. 310-321. American Society of Civil Engineers, New York.

Wheeler R. M. and Tibbitts T. W. (1987) Utilization of potatoes for life support systems in space. III. Productivity of successive harvest dates under 12-hour and 24-hour photoperiods. *Am. Potato J., 64*, 311-320.

Wittenberg L. J., Santarius J. F., and Kulcinski G. L. (1986) Lunar source of ^{3}He for commercial fusion power. *Fusion Technol., 10*, 167-178.

TECHNOLOGY DEVELOPMENT FOR LUNAR BASE WATER RECYCLING

N93-13999

John R. Schultz

KRUG International
1290 Hercules, Suite 120
Houston TX 77058

Richard L. Sauer

Mail Code SD 411
NASA Johnson Space Center
Houston TX 77058

INTRODUCTION

The establishment of a lunar base is being considered as one of the long-term goals of the U.S. Space Program. The proposed functions of such a facility include scientific research, exploitation of lunar resources, and development of a self-sufficient life support system. *Duke et al.* (1985) have discussed a phased approach for developing a lunar base. The first step would be the establishment of a lunar orbiting space station for preparatory exploration. The second phase would be the establishment of a small lunar surface research outpost based on space station technology. The next phase would be the development of an operational base for pilot-plant work on lunar agriculture and lunar material utilization. An advanced base would then follow that would emphasize oxygen production from lunar resources and research on closed ecological life support systems (CELSS). The final phase would be the development of a self-sufficient colony with an operational CELSS and full-scale oxygen production from lunar resources.

The development of a lunar base will require the development of processes to produce and recycle oxygen, food, and water. Closure of the life support system is necessary to reduce resupply requirements and associated costs as much as possible. The requirements for such a system have been outlined and discussed in several previous papers (*MacElroy et al.*, 1985; *Sauer*, 1985; *Spurlock and Modell*, 1979; *Spurlock et al.*, 1979). Since water is essential for maintaining life, the ability to recycle water will play an important role in maintaining a lunar base. Unfortunately, direct recycling of water for drinking is presently not performed to any great extent in terrestrial systems. In addition, many of the processes commonly used for water reclamation and purification on Earth may not be suitable for aerospace application because they are highly gravity dependent and require chemicals that need to be resupplied. NASA has recognized this problem and supported numerous research efforts aimed at developing water reclamation technology for aerospace applications. This paper will review previous and ongoing work in aerospace water recycling and identify research activities required to support development of a lunar base.

DISTILLATION PROCESSES

Much of NASA's water recycling research effort has focused on the development of distillation processes. Unfortunately, the processes commonly used on Earth are highly gravity dependent and need modifications for use in microgravity conditions. Processes currently under development to overcome this problem include vapor compression distillation, thermoelectric integrated membrane evaporation, and wick evaporation.

Vapor Compression Distillation

One process being developed to reclaim water from urine is vapor compression distillation (VCD). This process consists of a rotating still that recovers water by evaporation at subatmospheric pressure followed by compression and condensation of the resulting water vapor (*Zdankiewicz and Chu*, 1986). To reduce heat requirements, the process is arranged so that the heat flux from the condenser is used to evaporate the water. This results in a process with high water recoveries and low power consumption. Unfortunately, the recovered water does not meet NASA potable water standards for ammonia and volatile organics without additional pre- and post-treatment processes (*Slavin et al.*, 1986).

TIMES

The thermoelectric integrated membrane evaporation system (TIMES) is being developed by Hamilton Standard (*Dehner and Price*, 1987). In this process, water is passed through a hollow fiber membrane device at subatmospheric pressure. The water to be recovered diffuses through the membrane as a vapor. The water vapor is then recovered with a porous plate condenser. A thermoelectric device is used to recover the latent heat of condensation. Similar to the VCD process, this process has high water recoveries and low power consumption; however, it cannot process solids and also has problems with ammonia and volatile organics (*Slavin et al.*, 1986).

Wick Evaporation System

Another system being developed is the wick evaporation system (*Hall,* 1973). In this process, water is fed into an assembly consisting of a series of rayon felt wicks. The water is then evaporated by a heated air stream that passes through the wicks leaving the contaminants behind. The water vapor is then recovered with a condenser and a centrifugal air-water separator. This process has been used in previous 60- and 90-day manned chamber tests conducted by *McDonnell Douglas* (1968, 1970) in the late 1960s and the early 1970s. This process also requires the use of pre- and post-treatment processes to meet water quality standards. Current work with this process is aimed at simplifying operation and reducing energy requirements (*Morasko et al.,* 1986).

VPCAR

The vapor phase catalytic ammonia removal system (VPCAR) was developed to overcome the problems that ammonia and volatile organics carry over from distillation processes (*Budininkas et al.,* 1986). This process consists of a hollow fiber membrane evaporator followed by two catalytic reactors to convert ammonia to nitrogen and volatile organics to carbon dioxide. After passage through the reactors, the water vapor is recovered with a condenser. Unfortunately, this process is not capable of handling solids and has higher cost, volume, and power requirements than the VCD or TIMES processes.

The above processes are more complex and costly than terrestrial systems because of the requirement to work under microgravity conditions. Fortunately, this requirement will not be necessary for a lunar base application. The $\frac{1}{6}$ *g* at the lunar surface should allow development of an air-liquid interface and may allow simpler and less costly terrestrial distillation processes to be used. The problems with low removals of ammonia and volatile organics, however, will still remain. Thus, research on developing and evaluating distillation systems that operate under lunar surface conditions needs to be initiated.

MEMBRANE PROCESSES

The phase-change processes described above are primarily being developed to treat highly contaminated wastewaters such as urine. Because of their high energy requirements, these processes are thought to be nonoptimal for treating shower, personal hygiene, and housekeeping wash waters. Since these wash waters may contain low concentrations of high-molecular-weight compounds, the use of membrane processes is considered a viable alternative. The two membrane processes that appear most suitable for aerospace applications are reverse osmosis (RO) and ultrafiltration (UF). Ultrafiltration is mainly a filtration process that rejects suspended solids and macromolecules but allows low-molecular-weight salts to pass through the membrane. Reverse osmosis, however, rejects all suspended solids, macromolecules, and most of the low-molecular-weight salts.

Studies by Bend Research (*Ray et al.,* 1986) indicate that a two-stage RO system could be successfully used to treat a synthetic wash water. Further development work has emphasized the use of UF processes as a pretreatment for RO (*McCray et al.,* 1987). A study on using RO to recover actual shower water has also been conducted (*Verostko et al.,* 1987). The results indicate that an RO process followed by multifiltration posttreatment was able to provide water acceptable for hygiene use.

With respect to lunar base applications, the disadvantages of membrane systems include the production of a waste brine solution and the need to periodically replace the membranes. The waste brines are produced because membrane processes are normally operated in a cross-flow mode to minimize fouling. The problem with the waste brine may be reduced by increasing water recoveries or by processing the brines with a combustion process as discussed later.

PRETREATMENT PROCESSES

A major problem with most of the phase-change processes discussed above is their inability to remove ammonia and volatile organics. Various pretreatment chemicals have been investigated to overcome this problem. The addition of sulfuric acid and oxone has been used to fix free ammonia in shower water and prevent its carry-over in TIMES distillate (*Verostko et al.,* 1986). Unfortunately, the use of oxone has been shown to produce more volatile organics in urine distillate (*Putnam et al.,* 1986). In this case, better results have been obtained with nonoxidizing chemicals such as hexadecyl trimethyl ammonium bromide (HDAB) or a copper/chromium metal mixture. With respect to a lunar base, the use of pretreatment chemicals will require that they be periodically resupplied from Earth. This will make their use undesirable at a lunar base. Thus, research on developing alternate pretreatment processes such as biological, chemical, or electrochemical oxidation needs to be initiated.

MULTIFILTRATION

The most commonly used process for polishing product water from distillation and membrane processes is multifiltration. Multifiltration consists of a train of sorption beds containing various ion exchange, activated carbon, and polymeric resins in series. This system has been shown to be effective for polishing both distillation and RO product waters (*Verostko et al.,* 1986, 1987). Unfortunately, the resins have a finite lifetime and need to be periodically replaced as they are exhausted. Current work is emphasizing the development of a unibed consisting of a single canister containing the various sorbents packed in series. This approach is aimed at eliminating the requirement for maintaining a large inventory of spare resins for changeout.

With respect to a lunar base, the need to replace the sorbent beds presents some problems. A completely self-sufficient base will require the development of methods to regenerate the sorbents. Ion exchange resins can be regenerated with strong acid or base solutions. Activated carbon is usually regenerated with a high-temperature furnace. Research developing and evaluating these techniques for lunar base use is needed. The use of alternate processes for polishing the water also needs to be investigated.

DISINFECTION PROCESSESS

Microbial contamination is a major concern with terrestrial water systems. Water treatment processes such as filters, carbon adsorption beds, and ion exchange resins can encourage microbial contamination of the system by nutrient enrichment. Furthermore, virtually all system surfaces in contact with the water may become colonized by biofilm formation. Thus, water supply systems can be a source of disease if the water is not properly treated and the system properly maintained.

Microbial control is usually accomplished by the addition of chemicals to disinfect the water. Although chlorine is commonly

used in terrestrial systems, it is not currently being used in the space shuttle potable water system (*Willis and Schultz,* 1987). Instead, iodine is used because it has a lower vapor pressure than chlorine and can be easily added with an iodinated ion exchange resin called a microbial check valve (*Columbo et al.,* 1981). The use of iodine, however, is not without problems. The long-term health effects of ingestion of iodinated water are unknown (*Bull,* 1987). Iodine may react with trace organics to form halogenated organics, which have been implicated in cancer formation (*Janik et al.,* 1987). Various bacteria have been shown to develop a resistance to iodine action (*McFeters and Pyle,* 1987). Finally, iodine may impart an unpleasant taste to the water (*Willis and Schultz,* 1987).

Another disinfection technique that has been investigated for aerospace applications is heat. During manned chamber tests conducted in the late 1960s, disinfection was accomplished by holding water at 72°C for 6 hr (*McDonnell Douglas,* 1968). Temperature "spiking" has also been used for controlling microbial growth in RO systems (*Ray et al.,* 1986). The advantages of using heat are its applicability to all types of organisms, its sensitivity to chemical interferences, its effectiveness in the presence of particulates and biofilms, and its nondependence on expendable materials. The disadvantages, however, include high energy requirements and the lack of applicability to cold water (*Columbo and Sauer,* 1987).

Ultraviolet irradiation has also been evaluated in several studies (*Hall,* 1973; *Putnam et al.,* 1986). Although this method has been successful in reducing bacterial counts, it does not leave a residual disinfectant for controlling growth in the distribution system and must be used with other disinfectants. It also has higher power requirements than chemical addition methods such as iodine (*Columbo and Sauer,* 1987).

The use of ozone in terrestrial water systems has been steadily increasing over the past decade. Its possible use on the space station has not been pursued because of the need to develop microgravity gas-liquid contacting and separation processes, the high energy associated with its formation, and its potential for causing an offgas problem. The microgravity compatibility problem, however, will be reduced in the lunar environment.

With respect to lunar base application, a major problem with chemical disinfectants such as iodine will be the need to periodically resupply the chemical. Thus, a research program aimed at developing iodine recovery methods and alternate disinfectants is needed. The health effects due to possible buildup of iodide and iodinated by-products also needs to be evaluated. To reduce the potential for developing iodine-resistant bacteria, the use of at least two disinfection methods has been recommended (*Willis and Bull,* 1987). The development of point-of-use deiodinators to reduce taste and potential health problems also needs to be explored.

COMBUSTION PROCESSES

The phase-change processes being developed for the space station are mainly aimed at recovering water from liquid wastes only. To close the recycle loop and reduce resupply requirements, it will be necessary to also process solid wastes. Candidate processes that have been examined to accomplish this include incineration, wet oxidation, and supercritical water oxidation.

Incineration

The use of incineration has been evaluated by both GARD and GE in the early 1970s (*Slavin et al.,* 1986; *Murray and Sauer,* 1986). Both efforts resulted in the development of prototype units that were subjected to long-term tests. These systems require preconcentration of solids. They also produce very dirty effluent gas streams requiring posttreatment by catalytic oxidation. Successful use of these systems will require further development with respect to microgravity compatibility and automatic operation.

Wet Oxidation

A wet oxidation process was evaluated by Lockheed in the early 1970s (*Slavin et al.,* 1986). This process involves the oxidation of both liquid and solid wastes at elevated temperatures (550°F) and pressure (2000 psia). Its advantages include the ability to handle liquid wastes without preconcentration, automatic operation, and the production of a sterile effluent. Disadvantages of this process include its high temperature and pressure operation and the production of a relatively dirty effluent stream requiring extensive posttreatment.

Supercritical Wet Oxidation

This process being developed by Modar involves the oxidation of aqueous wastes at a temperature of 250°C and a pressure of 250 atm. At these conditions, inorganic salts that are soluble in water are insoluble and will precipitate from solution (*Hall and Brewer,* 1986). Primary results show that aqueous solutions of urea and sodium chloride can be effectively treated with essentially complete conversion of carbon to CO_2 and nitrogen to N_2 and N_2O (*Hong et al.,* 1987). Its disadvantages include relatively high weight, volume, and power requirements due to its high operating temperature and pressure.

BIOLOGICAL PROCESSES

Biological processes are commonly used in terrestrial wastewater reclamation systems because they are more efficient than physical or chemical processes. Unfortunately, these processes are very gravity dependent and major development work will be required to make them zero-*g* compatible. These processes also have slow response times, which can cause problems if they malfunction; thus, biological processes are presently perceived as too unreliable for the space station life support system, and very little development work has been done in the past. A lunar base, however, will be in a $\frac{1}{6}$-*g* environment, and the application of terrestrial biological processes might be feasible. To insure that adequate technology is available for lunar base development, evaluation of such processes needs to be initiated. Particular attention needs to be aimed at both carbon and ammonia oxidation processes using fixed film configurations.

NUTRIENT RECOVERY PROCESSES

The operation of plant growth systems at a lunar base will require the addition of nutrients such as nitrogen, phosphorus, and other minerals. Initial systems will probably use stored nutrient solutions that will have to be resupplied. To reduce these resupply requirements, the recovery and recycling of various nutrients is highly desirable. Very little work has been done on developing such systems. *Meissner and Model* (1979) have discussed processing schemes for removing sodium chloride from ash produced by total oxidation systems. One potential source for recovering these nutrients will be the various wastewater streams. Another possible method for recycling nutrients is the direct

application of wastewater to the plant system. Although this has been done in terrestrial systems, lunar base applications may require some development because of the reduced gravity, different soil, and more concentrated waste streams. A third method would be the separate recovery of nutrients such as ammonia and phosphates using ion exchange processes. This would also require considerable development work.

WATER QUALITY MONITORING

Total Organic Carbon

Another area that will need a major development effort is instrumentation to monitor and control water quality. Many of the instruments presently used in terrestrial laboratories are very gravity dependent and will require extensive modification for in-flight use. Several concepts have been explored for monitoring total organic carbon (TOC) in water, including ultraviolet absorbance, high-temperature combustion, and chemical oxidation (*Small,* 1987). The persulfate oxidation method has the capability of measuring organics at the 10 ppb level, but, unfortunately, requires a sparging vessel that is not microgravity compatible (*Modar,* 1984).

Specific Organics

Measurement of total organic carbon does not guarantee a water is safe to use. The identification and quantification of specific organics is also needed because ingestion of trace amounts of some organics can be hazardous. *Zlatkis* (1986) has reviewed the state of the art for measuring specific organics and proposed the use of a gas chromatograph system with either a photoionization or far ultraviolet detector. A purge-and-trap device would be used to concentrate and inject the organics into the gas chromatograph. Unfortunately, the microgravity incompatibility of present purge-and-trap methods was not discussed. Another problem with a gas chromatography system is that it may only be capable of accounting for 10% to 30% of the organics in reclaimed water (*Verostko et al.,* 1986, 1987).

Specific Inorganics

Inorganic compounds include many essential nutrients and trace metals. Some of these compounds can be hazardous at concentrations lower than would be detected by conductivity measurements. The state-of-the-art method for measuring trace amounts of metals is atomic absorption spectrometry. Unfortunately, this method has large power and expendable requirements. Also, it is not capable of measuring many of the common anions. Alternative methods that may be used for measuring specific inorganics include ion chromatography and ion selective electrodes. Ion chromatography is capable of measuring many common anions, cations, and trace metals, but requires the use of expendable solvents.

Microbial Contaminants

In order to verify the microbial quality of the reycled water, it will be necessary to develop methods for in-flight sampling and enumeration of contaminating bacteria. Present methods for enumerating bacteria in terrestrial water systems include membrane filter and plate count techniques. The major disadvantage of these methods is the requirement for several days of incubation prior to counting. A faster method being investigated is epifluorescence microscopy (*Pierson and Brown,* 1987). Regardless of the enumeration technique, a capability for in-flight identification of the bacteria must exist to support decisions on the potability of the water in the event of contamination. Automated biochemical methods are presently being developed to accomplish this task (*Pierson and Brown,* 1987). Although this technology appears to be promising, its applicability for detecting pathogens in water still needs to be demonstrated.

INTEGRATED SYSTEMS

Manned Chamber Tests

The feasibility of using a regenerative life support system based on physical and chemical processes has been demonstrated in 60- and 90-day manned chamber tests conducted by McDonnell Douglas in 1968 and 1970, respectively (*McDonnell Douglas,* 1968, 1970). As shown in Fig. 1, potable water was reclaimed from both urine and humidity condensate. The recovery system consisted of a wick evaporator process followed by a multifiltration system. Disinfection of the potable water was accomplished by heating, membrane filtration, and silver addition. This system produced water suitable for crew consumption in 57 out of 60 days during the 60-day test and throughout the 90-day test. Wash water was recovered by using a multifiltration system as shown in Fig. 2. Microbial control consisted of ultraviolet irradiation before the multifiltration unit and heating of the product water. Microbial analyses conducted during the 60-day test indicated this system could not maintain sterility of the recovered water. The use of the contaminated water, however, did not produce any adverse effects.

Space Station ECLSS

The present plans for the space station Environmental Control and Life Support System (ECLSS) are shown in Fig. 3 (*Ray and Humphries,* 1986). Humidity condensate will serve as the source of potable water. Urine and wash water will serve as the source of hygiene water. Fecal matter is presently not considered a practical water source because of the small amount of water in feces and the relative difficulty in reclaiming this water. Separate recovery systems will be developed for each source of water. The exact processes to be used in each subsystem have still not been specified but will consist of physical or chemical processes. Subsystem configurations presently being considered are shown in Fig. 4. Although testing of several of the processes and subsystems has been conducted, integrated testing of the overall system has yet to be completed. Such tests are presently planned for the early 1990s (*Moses et al.,* 1987).

Integrated Waste and Water Management System

The initial space station ECLSS will not process feces and other solid wastes. During the early 1970s, GE developed a system capable of handling such wastes called the Integrated Waste and Water Management System (IWWMS) (*Murray and Sauer,* 1986). As shown in Fig. 5, this system consists of evaporation followed by catalytic oxidation to recover potable water. The dried solids were then incinerated to produce a sterile ash. This system was successfully operated for 206 days using a 4-man equivalent of urine, feces, wash water, condensate, and trash. The prototype system has been recently donated to Texas A&M University, which plans to resume development of the system.

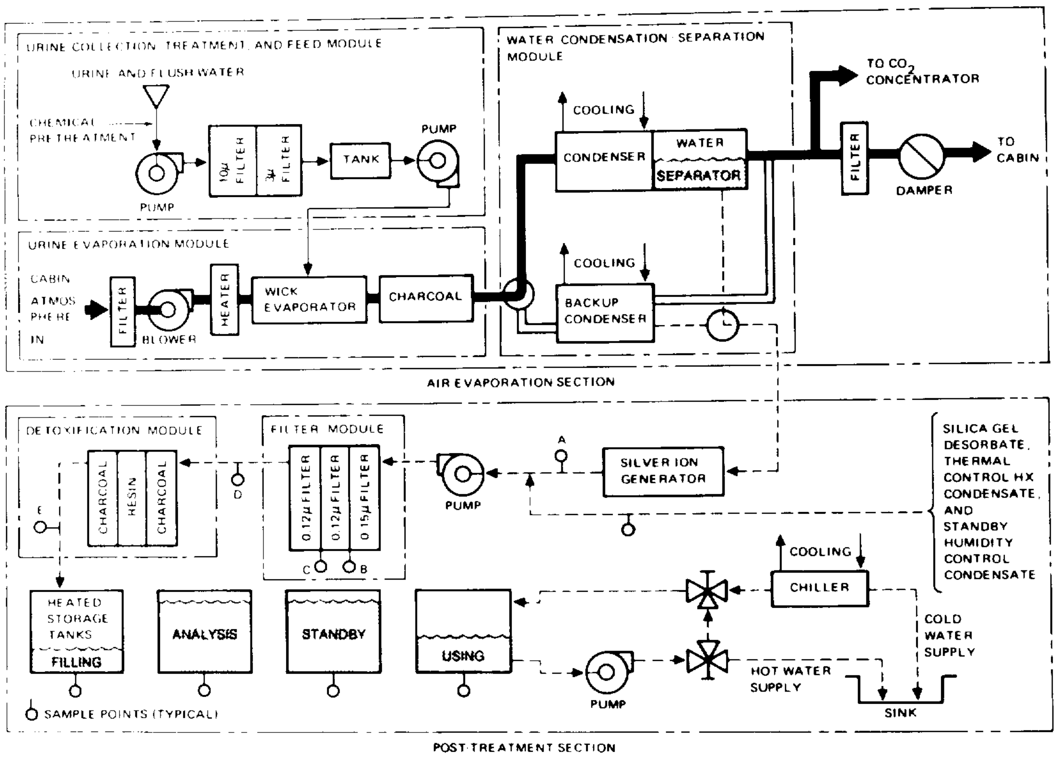


Fig. 1. Potable water recovery subsystem used in McDonnell Douglas tests.

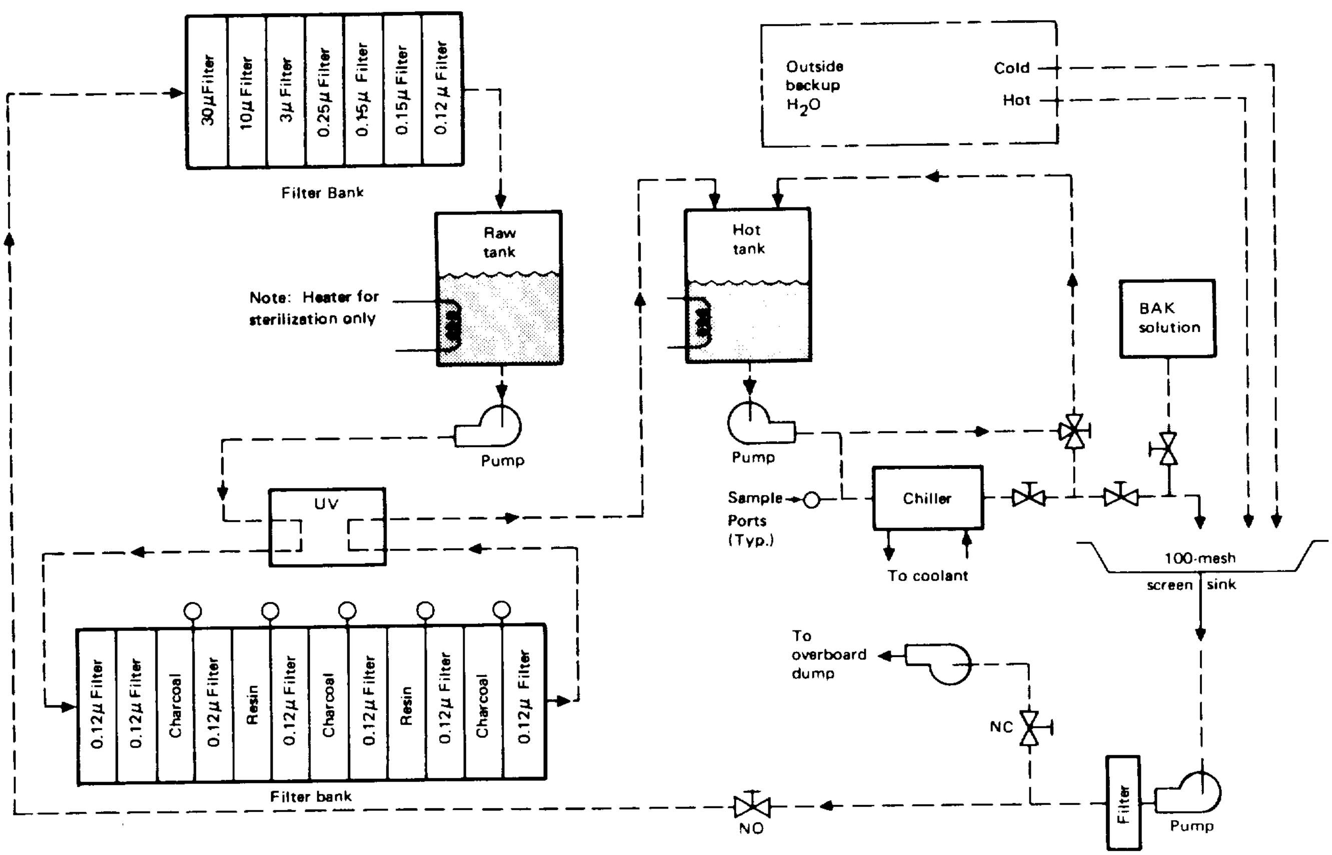


Fig. 2. Wash water recovery subsystem used in McDonnell Douglas tests.

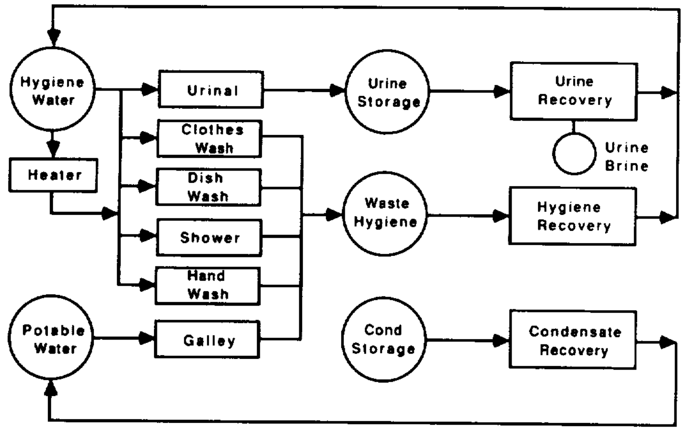


Fig. 3. Proposed space station ECLSS water reclamation system.

Closed Ecological Life Support Systems

NASA has recently initiated a program aimed at developing a CELSS, which incorporates subsystems for food production and nutrient recovery. Figure 6 shows how these subsystems may be integrated into the IWWMS to develop a bioregenerative lunar base life support system. This system is based on the development of plant growth modules to produce food and to generate oxygen. An effort to develop such modules has been initiated at the Kennedy Space Center (*Prince et al.,* 1987). Initial work is being conducted with wheat and other crop plants. The use of algae has also been proposed (*Ward and Miller,* 1984; *Holtzapple et al.,* 1988). This plant requires less volume and energy for growth than crop plants but contains less edible material. The goal of this program is to develop a breadboard CELSS to demonstrate the feasibility of the concept studies examining the chemical cycles involved. Such ground-based testing of the integrated system is necessary to certify the reliability of the equipment.

SUMMARY

The development of a water recycle system for use in the life support systems envisioned for a lunar base will require considerable research work. A review of previous work on aerospace water recycle systems indicates that more efficient physical and chemical processes are needed to reduce expendable and power requirements. Development work on biological processes that can be applied to microgravity and lunar environments also needs to be initiated. Biological processes are inherently more efficient than physical and chemical processes and may be used to minimize resupply and waste disposal requirements. Processes for recovering and recycling nutrients such as nitrogen, phosphorus, and sulfur also need to be developed to support plant growth units. The development of efficient water quality monitors to be used for process control and environmental monitoring also

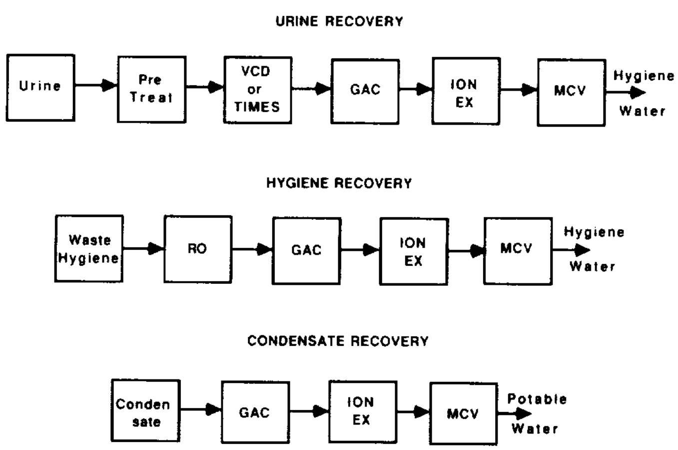


Fig. 4. Candidate subsystem configurations for ECLSS water reclamation.

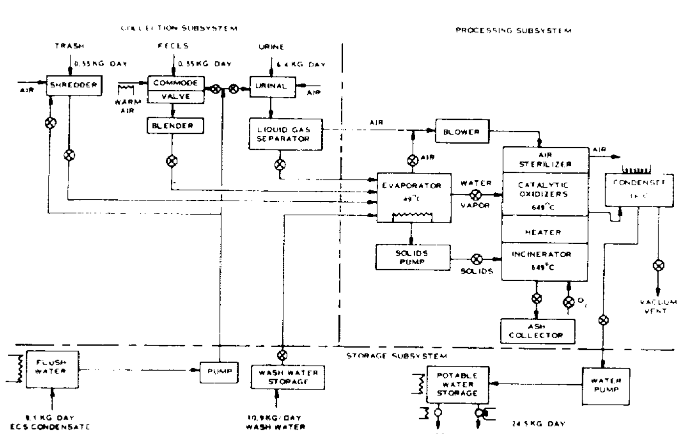


Fig. 5. Integrated waste and water management system (IWWMS).

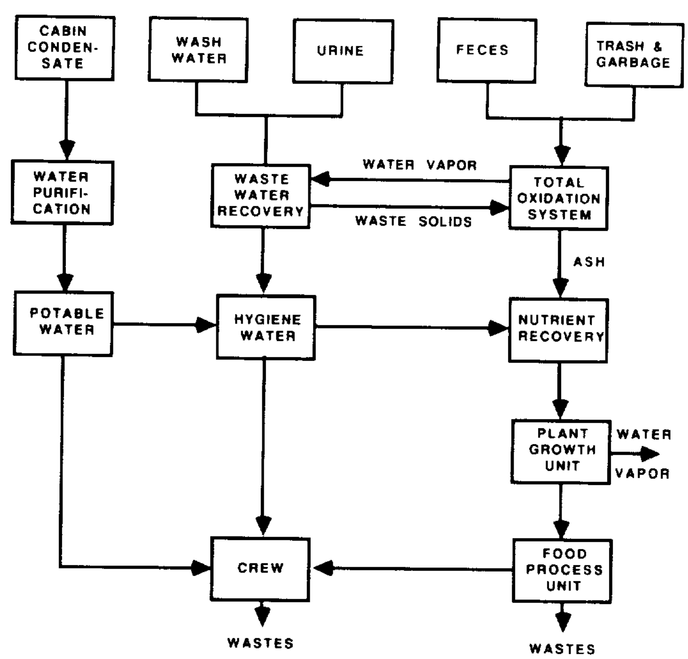


Fig. 6. Advanced lunar base water reclamation system.

needs to be initiated. Present methods require extensive instrumentation, highly trained personnel, and large space requirements that will not be available at a lunar base. The review also indicates very little integrated testing of advanced life support systems has been done. Although expensive, such testing is necessary to demonstrate the feasibility of such systems, examine interactions between the processes, and evaluate potential environmental health hazards.

REFERENCES

Budininkas P. et al. (1986) Development of a water recovery subsystem based on vapor phase catalytic ammonia removal (VPCAR). *16th Intersociety Conference on Environmental Systems,* SAE Paper 860985. San Diego, California.

Bull R. J. (1987) Toxicological aspects of water recycle and disinfection. *17th Intersociety Conference on Environmental Systems,* SAE Paper 871491. Seattle, Washington.

Columbo G. V. and Sauer R. L. (1987) Review of water disinfection technology. *17th Intersociety Conference on Environmental Systems,* SAE Paper 871488. Seattle, Washington.

Columbo G. V. et al. (1981) Advanced microbial check valve development. *11th Intersociety Conference on Environmental Systems,* ASME Paper 81-ENAs-45. San Francisco, California.

Dehner G. F. and Price D. F. (1987) Thermoelectric integrated membrane evaporation subsystem testing. *17th Intersociety Conference on Environmental Systems,* SAE Paper 871446. Seattle, Washington.

Duke M. B., Mendell W. W., and Roberts B. B. (1985) Strategies for a permanent lunar base. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 57-68. Lunar and Planetary Institute, Houston.

Hall J. B. (1973) *Domestic Wash-Water Reclamation Using an Aerospace Developed Water Recovery Subsystem.* NASA-TM-X-2896.

Hall J. B. and Brewer D. B. (1986) Supercritical water oxidation: Concept analysis for evolutionary space station application. *16th Intersociety Conference on Environmental Systems,* SAE Paper 860993. San Diego, California.

Holtzapple M. T. et al. (1988) Analysis of an algae-based CELSS. In *Papers Presented to the Controlled Environmental Life Support Systems Research Conference.* Texas A&M University, College Station, Texas.

Hong G. T. et al. (1987) Supercritical water oxidation: Treatment of human waste and system configuration tradeoff study. *17th Intersociety Conference on Environmental Systems,* SAE Paper 871444. Seattle, Washington.

Janik D. S. et al. (1987) Medical effects of iodine disinfection products in spacecraft water. *17th Intersociety Conference on Environmental Systems,* SAE Paper 871490. Seattle, Washington.

MacElroy R. D., Klein H. P., and Averner H. M. (1985) The evolution of CELSS for lunar bases. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 623-633. Lunar and Planetary Institute, Houston.

McCray S. B. et al. (1987) Development of a non-phase-change wastewater treatment subsystem. *17th Intersociety Conference on Environmental Systems,* SAE Paper 871514. Seattle, Washington.

McDonnell Douglas Astronautics Company (1968) *60-Day Manned Test of a Regenerative Life Support System with Oxygen and Water Recovery.* NASA CR-98500.

McDonnell Douglas Astronautics Company (1971) *Operational Ninety-Day Manned Test of a Regenerative Life Support System.* NASA CR-111881.

McFeters G. A. and Pyle B. H. (1987) Consequences of bacterial resistance to disinfection by iodine in potable water. *17th Intersociety Conference on Environmental Systems,* SAE Paper 871489. Seattle, Washington.

Meissner H. P. and Modell M. (1979) Recycling plant, human and animal wastes to plant nutrients in a closed ecological system. *9th Intersociety Conference on Environmental Systems,* ASME Paper 79-ENAs-29. San Francisco, California.

Modar, Inc. (1984) *Evaluation of Organic Carbon Analyzers for Space Applications.* NASA Report NAS9-16675.

Morasko G. et al. (1986) Air evaporation closed cycle water recovery technology—Advanced energy saving designs. *16th Intersociety Conference on Environmental Systems,* SAE Paper 860987. San Diego, California.

Moses W. et al. (1987) Performance characterization of a waste/water recovery system. In *Papers Presented to the Controlled Environmental Life Support Systems Research Conference.* Texas A&M University, College Station, Texas.

Murray R. W. and Sauer R. L. (1986) Integrated waste and water management system. *16th Intersociety Conference on Environmental Systems,* SAE Paper 860996. San Diego, California.

Pierson D. L. and Brown H. D. (1987) Inflight microbial analysis technology. *17th Intersociety Conference on Environmental Systems,* SAE Paper 871493. Seattle, Washington.

Prince R. P. et al. (1987) Design and performance of the KSC biomass production chamber. *17th Intersociety Conference on Environmental Systems,* SAE Paper 871437. Seattle, Washington.

Putnam D. F. et al. (1986) Pre- and post-treatment techniques for spacecraft water recovery. *16th Intersociety Conference on Environmental Systems,* SAE Paper 860982. San Diego, California.

Ray C. D. and Humphries W. R. (1986) Status of the space station environmental control and life support system design concept. *16th Intersociety Conference on Environmental Systems,* SAE Paper 860943. San Diego, California.

Ray R. J. et al. (1986) A membrane-based subsystem for very high recoveries of spacecraft waste waters. *16th Intersociety Conference on Environmental Systems,* SAE Paper 860984. San Diego, California.

Sauer R. L. (1985) Metabolic support for a lunar base. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 647-651. Lunar and Planetary Institute, Houston.

Slavin T. J. et al. (1986) CELSS waste management systems evaluation. *16th Intersociety Conference on Environmental Systems,* SAE Paper 860997. San Diego, California.

Small J. W. (1987) Recent developments in water quality monitoring for space station reclaimed wastewaters. *17th Intersociety Conference on Environmental Systems,* SAE Paper 871547. Seattle, Washington.

Spurlock J. and Modell M. (1979) Systems engineering overview for regenerative life-support systems applicable to space habitats. In *Space Resources and Space Settlements.* NASA SP-428.

Spurlock J. et al. (1979) Research planning criteria for regenerative life-support systems applicable to space habitats. In *Space Resources and Space Settlements.* NASA SP-428.

Verostko C. E. et al. (1986) Results on reuse of reclaimed shower water. *16th Intersociety Conference on Environmental Systems,* SAE Paper 860983. San Diego, California.

Verostko C. E. et al. (1987) Test results of a shower water recovery system. *17th Intersociety Conference on Environmental Systems,* SAE Paper 871512. Seattle, Washington.

Ward C. H. and Miller R. L. (1984) Algal bioregenerative systems for space life support. *The Physiologist, 27,* S-21.

Willis C. E. and Bull R. J. (1987) *Space Station Water Quality Conference Report.* NASA JSC-32024.

Willis C. E. and Schultz J. R. (1987) Spacecraft water system disinfection technology: Past, present and future needs. *17th Intersociety Conference on Environmental Systems,* SAE Paper 871487. Seattle, Washington.

Zdankiewicz E. M. and Chu J. (1986) Phase change water recovery for space station—Parametric testing and analysis. *16th Intersociety Conference on Environmental Systems,* SAE Paper 860986. San Diego, California.

Zlatkis A. (1986) *Organics in Water Contamination Analyzer.* NASA CR-179901, Ionics Research Inc.

٥

٣

PLASMA REACTOR WASTE MANAGEMENT SYSTEMS

Robert O. Ness Jr., John R. Rindt, and Sumitra R. Ness

University of North Dakota
Energy and Environmental Research Center
P.O. Box 8213
University Station
Grand Forks ND 58202

The University of North Dakota is developing a plasma reactor system for use in closed-loop processing that includes biological, materials, manufacturing, and waste processing. Direct-current, high-frequency, or microwave discharges will be used to produce plasmas for the treatment of materials. The plasma reactors offer several advantages over other systems, including low operating temperatures, low operating pressures, mechanical simplicity, and relatively safe operation. Human fecal material, sunflowers, oats, soybeans, and plastic were oxidized in a batch plasma reactor. Over 98% of the organic material was converted to gaseous products. The solids were then analyzed and a large amount of water and acid-soluble materials were detected. These materials could possibly be used as nutrients for biological systems.

INTRODUCTION

With the launching of the U.S. space station scheduled for the mid-1990s, the likelihood of longer manned missions to the Moon and Mars, and eventual lunar and martian bases, there is a need to develop more comprehensive Environmental Control/Life Support Systems (ECLSS) for use in extraterrestrial activities. Both energy and physical size requirements will dictate the type of ECLSS that will be necessary. Three options are available for extended space living, including (1) systems in which consumables such as oxygen and food are not recycled; (2) totally closed-loop systems with recovery of all consumables; or (3) partially closed systems. The decision regarding the percentage of consumable material that will be recycled will be based primarily on the size and energy requirements of the closed-loop system.

Environmental Control/Life Support Systems, as they exist in current spacecraft, are primarily concerned with subsystems that will provide life support. The raw materials for these systems have been self-contained and, to a large extent, not recycled. For larger systems, such as bases, the processing must be expanded to allow manufacturing, materials handling, and waste treatment. The interaction between the groups (biological, materials, manufacturing, and waste processing) in the closed-loop processing (CLP) resource management system is illustrated by Fig. 1.

The primary objective of this research program at the University of North Dakota is to develop the application of low-temperature plasma reactor systems to closed-loop processing. Closed-loop processes are those that require essentially no raw materials, while producing little or no by-product or waste. Typical applications of these systems are those that will be used in either remote processing or habitation communities such as isolated research communities, both terrestrially and in space.

The systems that will be used on the lunar surface will integrate the biological systems and the material processing systems as closely as possible. A plasma reactor could be a central processing unit that will serve to integrate the operation of waste treatment, biological processing, materials processing, and manufacturing, all of which are being conducted at a remote site where resupply and waste disposal are impossible, or at least difficult and costly.

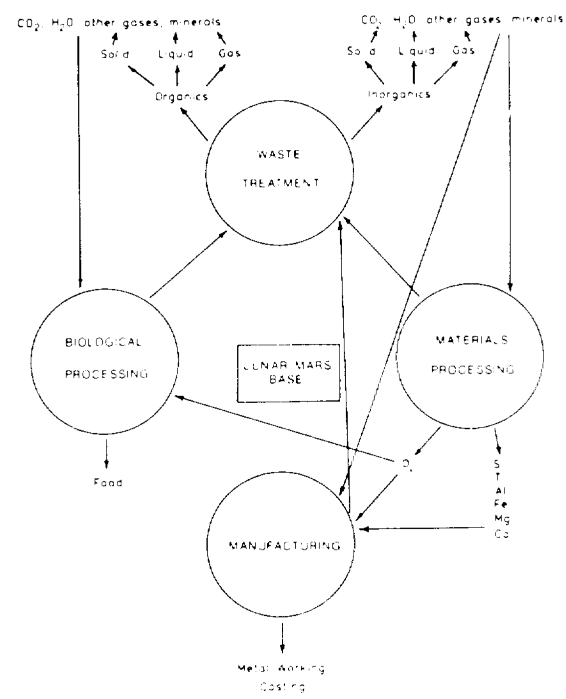


Fig. 1. Closed-loop processing (CLP) resource management system.

The intent of the project and future research is to pass products from one or more of the CLP areas to another in which they will serve as reactants.

BASIC PLASMA GENERATION

A plasma is a highly ionized gas that is electrically neutral and composed of ions, electrons, and neutral particles. The various species are formed when gas molecules acquire energy by intermolecular collisions or from electromagnetic radiation.

There are three basic methods of plasma generation: (1) direct thermal; (2) direct-current discharges; and (3) high-frequency discharges. Figure 2 is a block diagram summarizing the generation types. Each pertinent group will be discussed in the following paragraphs.

Direct-current (dc) and high-frequency discharge both produce ions by one or a combination of two mechanisms: (1) molecular absorption of photons and (2) inelastic electron-molecular collisions. These reactions occur simultaneously, in equilibrium, with the termination reactions that include (1) desorption of a photon, (2) elastic electron-molecular collision, and (3) reaction of the ion with other molecules to form new compounds.

The first initiation mechanism is the molecular absorption of a photon (i.e., the Compton Effect; *Beiser,* 1981). The activated molecule may then react with other reactants to form products, such as ions, or it can release the energy by emitting a photon. When the products of these reactions are ions, the electromagnetic field will also provide kinetic energy to the ionic molecules, which in turn will promote the production of additional ions through collisions. Because a particular wavelength activates certain molecules, selective activation of a single species in a multicomponent system may be accomplished.

The second method of ionization is by electron-molecular collisions. The kinetic energy of the molecules is then increased by elastic electron-molecular collisions, while inelastic collisions lead to excitation, fragmentation, or ionization of the molecule. In every case, the rate at which the collisions occur per unit gas volume is directly proportional to the bulk gas pressure and the electron density (*Baddour and Timmins,* 1967, pp. 1, 55-59).

Either of the two mechanisms of ion production will promote the production of more ions. The mechanism that predominates will depend on electron temperature, bulk gas temperature, electric field intensity, and the concentration of molecules in the system.

UNIQUE ASPECTS OF PLASMA REACTOR SYSTEMS

Plasma reactors offer several characteristics that make them particularly attractive for use in space applications, where the ability to control the reactor and the moderate operating temperatures and pressures contribute to relatively safe operation. While engineering details change, the overall concept will work in both microgravity and gravity fields. Particular operating characteristics that contribute to the usefulness and safety of plasma reactors are

1. Reaction Specificity. The efficiency of energy transfer from the electromagnetic source to the parent gas molecules depends on the frequency of the radiation. Therefore, when a specific frequency is used, particular molecules will ionize and cause specific reactions to occur. With the ability to vary the frequency, the plasma reactor can be used for a variety of reactions, thus providing a very versatile system.

2. Reaction Rate Control. Because the rate of ion generation is directly related to electromagnetic field strength, the concentration of activated species and, consequently, the reaction rate can be very easily controlled.

3. Rapid Reactor and Reaction Shutdown. The ion production rate in the "ion generator" is inversely proportional to the concentration of reacting molecules in the system. Therefore, a hole or leak into the generator will result in an increase in system pressure, and the rate of ion production will decrease markedly. The result would be an orderly shutdown of the reacting system.

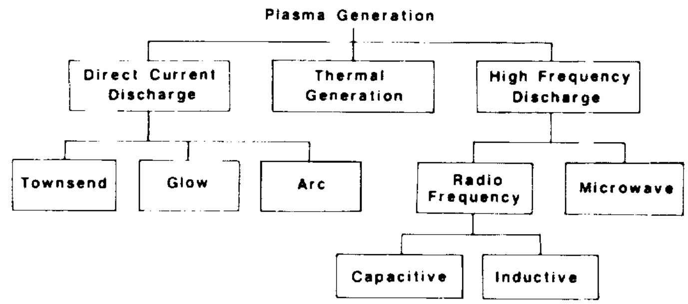


Fig. 2. Plasma generation techniques.

OXYGEN PLASMA WASTE CONVERSION (OPWC) RESEARCH

Preliminary testing of the feasibility of using oxygen plasma reactor systems for the removal of organics from waste material has just been completed. Samples of oats, sunflowers, freeze-dried human fecal waste, and a plastic bag (Baggie) were reacted in a batch oxygen plasma system. Table 1 shows an HCN (hydrogen-carbon-nitrogen) analysis of the material remaining in the reactor.

TABLE 1. Data summary for oxygen plasma waste conversion unit.

Freeze-dried Human Fecal Sample	
OPWC % Residue*	31.00
% Carbon	5.205 + 0.145
% Nitrogen	0.885 + 0.045
% Hydrogen	1.380 + 0.06
% Conversion‡	98.39
% 6M-HCl-Soluble	73.86
% Water-Soluble	32.33
Sunflower Root, Stalk, and Head Sample	
OPWC % Residue	18.52
HCN Analysis of Residue	
% Carbon	5.220 + 0.27
% Nitrogen	0.440 + 0.04
% Hydrogen	1.655 + 0.095
% Conversion	99.03
% Water-Soluble	82.36
Oat Root, Stalk, and Head Sample	
OPWC % Residue	11.15
HCN Analysis of Residue	
% Carbon	1.810 + 0.06
% Nitrogen	0.260 + 0.02
% Hydrogen	1.035 + 0.085
% Conversion	99.8
Soybean Root, Stalk, and Head Sample	
OPWC % Residue	17.45
HCN Analysis of Residue	
% Carbon	3.955 + 0.155
% Nitrogen	0.490 + 0.01
% Hydrogen	0.890 + 0.05
% Conversion	99.31
Plastic (Baggie) Sample	
OPWC % Residue	1.40
% Conversion	98.60

* (Weight of residue out of OPWC)/(weight of sample in OPWC).
† Standard HCN on a Control Equipment Corporation unit.
‡ 1-(OPWC residue - nonorganic weight)/(OPWC sample weight - nonorganic weight).

Conversion was based on the amount of C left in the sample and was defined as one minus the weight of inorganic free residue divided by the initial inorganic free sample weight. The carbon content was determined by a standard HCN analysis (*Control Equipment Corporation*). The human and plastic samples exhibited the lowest conversions of 98.4% and 98.6%, respectively.

Figure 3 shows the results of a simple residence time experiment completed using human fecal matter. Every two hours the sample was removed from the chamber, cooled in a desiccator, weighed, stirred, and replaced in the reactor. Stirring is necessary to remove any residue formed at the surface. Conversion takes place rapidly up to approximately 80% and then the rate of conversion declines.

Processing of the waste materials included two steps: dehydration and organic conversion. Figure 4 summarizes the composition of a typical fecal sample including the mass of water, material converted, water-soluble residue, and insoluble residue. The figure gives a perspective of the percentage of material the two steps need to handle. The dehydration and organic conversion step removed 99.56% of the material.

The remaining 0.0012 lb of inorganic material was evaluated by water and acid (HCl) solubility tests and X-ray diffraction and fluorescence analysis. Figure 5 shows the results of the solubility tests and Table 2 shows the X-ray fluorescence test results. These materials have amorphous structures since the X-ray diffraction analysis did not yield any crystalline structures above 5% of the total mass.

The X-ray fluorescence results verify the solubility test results. The only component that is readily soluble in water is P_2O_5, which decomposes. The solubility test indicated approximately 32% of the residue to be soluble, while the X-ray fluorescence indicates 31.7% of the material to be P_2O_5. The acid solubility tests also correspond. Magnesium oxide, Al_2O_3, P_2O_5, SO_3, CaO, and Fe_2O_3 are HCl soluble. The solubility test (83%) and the X-ray fluorescence (81.57%) indicate this relationship. Further tests are being done to determine potential end uses for this residue.

These figures show a systematic reduction of 99.56% of the material by dehydration followed by the conversion of an organic material. Since the primary goal of determining if an oxygen plasma system could process a quantity of materials with high conversion was achieved, further analysis of the products and process development is needed to determine electrical requirements, size, residence times for fluidized beds, etc. This information will determine feasibility for space use.

The gas stream from the oxygen plasma conversion unit was not analyzed. It is assumed that most of the gaseous products were CO_2; however, the gas stream from the plastic bag probably contained some chlorine compounds.

TABLE 2. Energy-dispersive X-ray analysis.

	RESULTS				
	Weight %	Std. Dev.		Oxide %	Std. Dev.
O	37.340				
Mg	3.319	0.044	MgO	5.504	0.072
Al	0.279	0.008	Al_2O	30.527	0.014
Si	1.330	0.010	SiO_2	2.844	0.022
P	13.840	0.040	P_2O_5	31.720	0.090
S	1.809	0.008	SO_3	4.516	0.021
Ca	27.800	0.100	CaO	38.900	0.140
K	6.917	0.049	K_2O	7.465	0.059
Ti	0.471	0.010	TiO_2	0.786	0.017
Fe	0.279	0.003	Fe_2O_3	0.399	0.004
TOTAL	92.660				

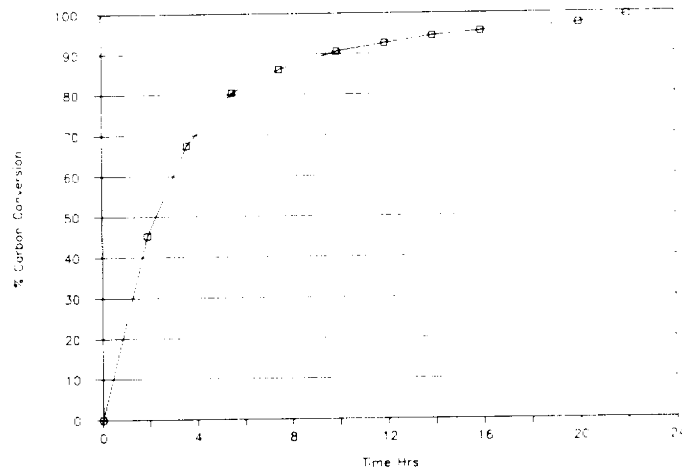


Fig. 3. Percent combustor carbon conversion.

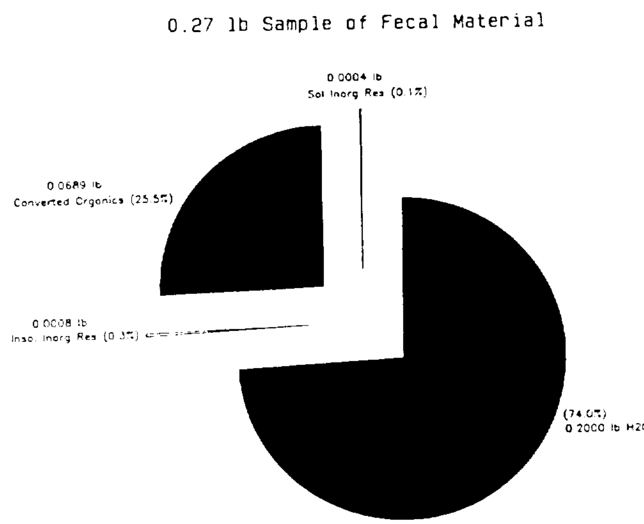


Fig. 4. Fecal sample composition.

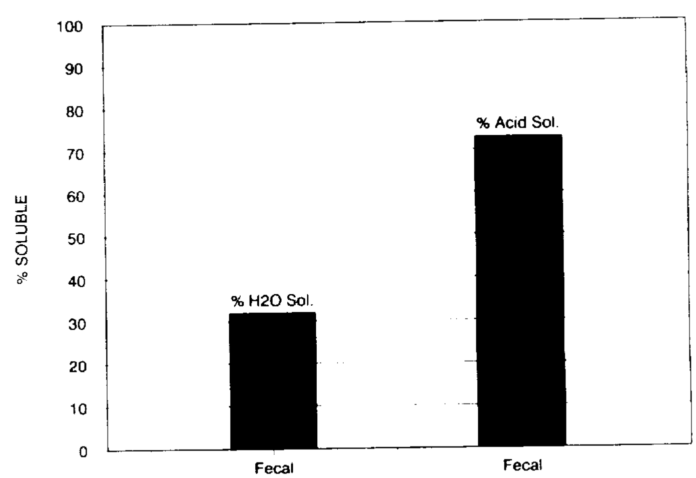


Fig. 5. Combustor residue solubility.

APPLICATIONS OF PLASMA REACTORS TO SPACE ENGINEERING SYSTEMS

A process flow diagram, as shown in Fig. 6, could be used to process waste material from a space station or lunar base. Similar processes have been proposed for terrestrial use, but because of relatively high electrical costs as compared with those of other biological processes, the systems were uneconomical. In space environments, factors other than electrical costs play important roles. This system could be either independent of a biological treatment system or in conjunction with such a system. These types of systems could complement each other because they could provide operating flexibility by changing electrical requirements, size, weight, residence time, and allow high conversion of all organic feed materials.

In terrestrial processes, the following technical and economical factors must be considered: (1) operating conditions (temperature, pressure, pH); (2) operating complexity; (3) equipment maintainability; (4) size; (5) weight; (6) electrical requirements; (7) storage of processing and processed materials; (8) location of raw materials; (9) heat rejection; and (10) safety. Due to the many operating restrictions, the plasma reactor system may have operational advantages over other schemes based on the following: (1) low operating temperatures; (2) low operating pressures; (3) mechanical simplicity; (4) can be used to process solids, liquids, and gases; (5) relatively safe operation; and (6) ease of operation.

A plasma reactor may oxidize or reduce specific components of a process stream while leaving the remainder of the stream unaffected. This, in effect, is a separation and conversion process taking place in one reactor. An example is the conversion of the organic fraction of plants, human waste, and plastics to gases while the inorganic fraction remains unchanged. The inorganic materials can then be directly recycled to other operations.

Plasma reactors are relatively simple to operate because they do not require high temperatures or pressures, or the addition of caustics or acids for chemical reactions. Aqueous solutions can be treated by using a microwave drying step before the oxidation step. Because the system operates under mild conditions, the plasma reactor may offer an alternative to high-temperature processes. The system does not require a heating or cooling period, so reactions can be very tightly controlled; this contributes to the efficiency and safety of the system.

Other applications for the use of plasma reactors could be in the reduction of lunar soils for the production of oxygen. Presently, researchers are thermally heating hydrogen to approximately 900°C and reducing ilmenite to Fe, TiO_2, and water (*Gibson and Knudsen,* 1985). The water is then electrolyzed to produce hydrogen and oxygen. Since this system requires the injection of large quantities of heat, which will require the presence of larger radiators on the lunar surface, reduction by a hydrogen plasma atmosphere may be practical. While this presents advantages in reducing process severity, there remain many technical questions that need to be addressed.

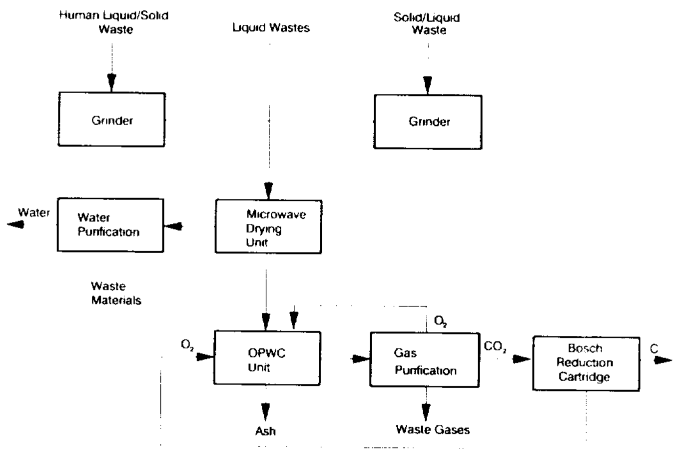


Fig. 6. Waste management process flow diagram .

REFERENCES

Baddour R. F. and Timmins R. S. (1967) *The Application of Plasmas to Chemical Processing.* Massachusetts Institute of Technology, Cambridge.

Beiser A. (1981) *Concepts of Modern Physics,* pp. 132-133. McGraw-Hill, New York.

Control Equipment Corporation (date unknown) *CHN Analysis Scheme.* Available upon request at the UND Energy and Environmental Research Center, Box 8213, University Station, Grand Forks ND 58202 (Phone 701-777-5000).

Gibson M. A. and Knudsen C. W. (1985) Lunar oxygen production from ilmenite. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 543-558. Lunar and Planetary Institute, Houston.

DISTRIBUTION OF HUMAN WASTE SAMPLES IN RELATION TO SIZING WASTE PROCESSING IN SPACE

N93-14001

Dick Parker

University of North Dakota
Grand Forks ND 58202

S. K. Gallagher

U.S. Department of Agriculture
Agricultural Research Service
Human Nutrition Research Center
Grand Forks ND 58202

INTRODUCTION

Human waste processing for closed ecological life support systems (CELSS) in space requires that there be an accurate knowledge of the quantity of wastes produced. Because initial CELSS will be handling relatively few individuals, it is important to know the variation that exists in the production of wastes rather than relying upon mean values that could result in undersizing equipment for a specific crew. On the other hand, because of the costs of orbiting equipment, it is important to design the equipment with a minimum of excess capacity because of the weight that extra capacity represents. We were fortunate to have available to us a considerable quantity of information that had been independently gathered on waste production; we examined that information in order to obtain estimates of equipment sizing requirements for handling waste loads from crews of 2 to 20 individuals.

METHODS

Overall, some 25,000 person days of data were available. These data were obtained from 15 metabolic studies conducted at the USDA Human Nutrition Research Center in Grand Forks, North Dakota. The 15 diets for these studies were designed to approximate diets consumed by typical Americans, and were fed in 3-day cycles. Intake was adjusted to maintain weight to within 2% of admission weight. To minimize the variability of composition, fresh fruit or vegetables were not used. Volunteers consumed only what was given to them by the metabolic kitchen. Volunteers were chaperoned at all times to assure nothing was eaten outside the laboratory and that collection of samples was complete.

All collection periods were from 0800 to 0800 (24 hours). Urine was collected in its entirety in large plastic containers that had an acid preservative. If a specimen was inadvertently missed, an estimate of the amount lost was made. Urine volumes were measured to within ±10 ml. Stool samples were collected in individual collection bags. Toilet tissue was not collected. Collection bags were preweighed within 0.05 g. Sample weights were obtained immediately after collection. Bag weights were subtracted from total weights to give wet weight. Individual samples were lypholized using standard freeze drying techniques. A dry weight minus bag weight was then obtained.

Menstrual samples were collected in 24-hour collection bags. Pads, tampons, or pantyliners were used. The weight of 20 of each lot number of products was used to calculate an average weight of the product. A complete as possible collection was obtained by cleaning genital areas with wet gauze; the gauze was added to the collection bag. A record of weights of water and gauze was kept. The number of products used for each 24-hour collection period was recorded. Wet and dry weights were collected and appropriate calculations for amount of menstrual fluids lost were performed.

RESULTS

A total of 25,171 person days of data were available. Sample collection problems, spilled samples, etc. produced smaller sample sizes for each analysis. Dry weight of stool samples was not measured during all experiments, hence this sample size is considerably smaller.

Stool

Stool sample data were available in both wet weight and dry weight. The number of bowel movements combined into a day's sample was also recorded.

Analysis of 24,888 24-hour stool samples gave a mean wet weight of 95.5 g per day (s.d. 95.7 g). A large part of the variation for the standard deviation resulted from no bowel movements 30% of the days (7581), and thus zero weight. The dotted line in Fig. 1a shows the distribution of these 24-hour samples. The solid line shows the distribution of individual mean values for 171 individuals. Much of the variation is caused by individual differences. Figure 1b shows the distribution of samples as a multiple of the individual's mean, thus presenting a measure of variation within individuals. The highest value was 25.6 for the size of one day's sample when divided by that individual's mean; this is equivalent to more than three weeks. This individual usually had one day a month with a 24-hour stool sample that exceeded

14 times the individual's mean. Values over four times the individual's mean were common among individuals.

Mean daily stool weight correlated ($p < 0.001$) with caloric intake, which is a measure of the quantity of food. However, the R2 value is only 0.28, indicating that 72% of the variation in individual means is not explained by the quantity of food eaten. Additional fiber in the diet is known to increase daily stool weight (*Tucker et al.,* 1981). The subjects in this study were on a relatively low-fiber diet, not unlike that eaten while in space.

The size of the stool sample produced on a given day is influenced by the size of the sample of the previous day, particularly by zero sample days. We made computer simulation runs of 100 days for crews of 2 to 20 individuals. One hundred days of data were available for 128 individuals in our sample. "Crews" were selected in sequence from this group, with each individual being used only once for a crew of each size from 2 to 20. Consequently we had 64 crews of 2 but only 6 crews of 20 individuals in our simulation runs. In a given run, the first day's waste quantity of all crew members was summed and the waste processor capacity subtracted from the total. If unprocessed waste remained, it was carried forward as "surge capacity," otherwise the next day started at zero. This was done sequentially for the 100 days. A variety of waste processor sizes was assumed, starting from just slightly larger than the mean (corrected for crew size) to 10 times the mean. The number of days not generating surge capacity was counted. In addition, the distribution of the surge capacity values was obtained. The processing capacity required in order to never need surge capacity and the capacity needed to use surge capacity on only 1% of the days is shown for the various crews in Fig. 1c. The mean is included in the figure for comparison purposes.

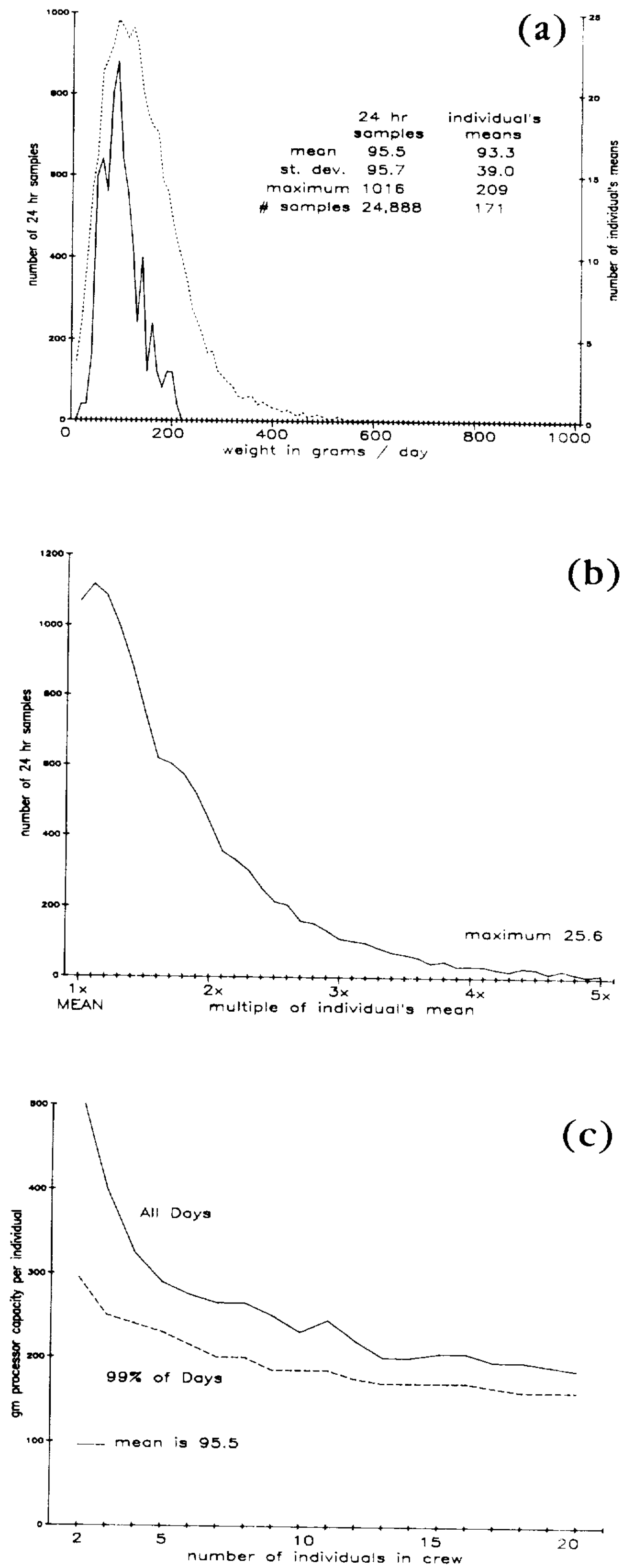


Fig. 1. 24-hour stool sample. **(a)** Dashed line is 24-hour samples, solid line is means of individuals. **(b)** Distribution of samples represented as a multiple of that individual's mean. The 43% of samples that exceed the mean are shown. **(c)** Required per-person stool processing capacity vs. crew size. The mean is included for comparison.

Dry Stool Weight

Dry stool weight was measured in 14,963 24-hour samples. The mean weight was 20.5 g per day (s.d. 19.5 g). The minimum was zero and maximum was 201.8 g. There were 4575 days with no movements; hence only 10,288 samples were actually dried. Figure 2a represents the distribution of 24-hour values (dashed line) and individual means (solid line). Figure 2b shows 24-hour values as a multiple of the individual's mean. The mean fraction of the sample remaining after drying is 0.25. Substantial variation, 0.15 to 0.40, existed between individuals. However, the mean value of individual means was similar at 0.26.

Results of simulation runs for crews of 2 to 20 persons are shown in Fig. 2c. The number of runs is based upon 100 days' data for 74 individuals; higher crew sizes are represented by only 3 runs.

Frequency of Bowel Movements

Individuals had bowel movements on 70% of the days. The mean number of bowel movements per day was 0.855. Individuals had a range of average number of movements between 0.21 and 2.54 movements per day. On 99% of the days individuals had 3 or fewer movements.

Urine

Analysis of 24,919 24-hour combined urine samples shows a mean value of 2066 ml (s.d. 1234). This value is 38% larger than the 1500 ml used in some other studies (*Schubert et al.,* 1985; *Slavin et al.,* 1986; *Nitta et al.,* 1985). Figure 3a shows the

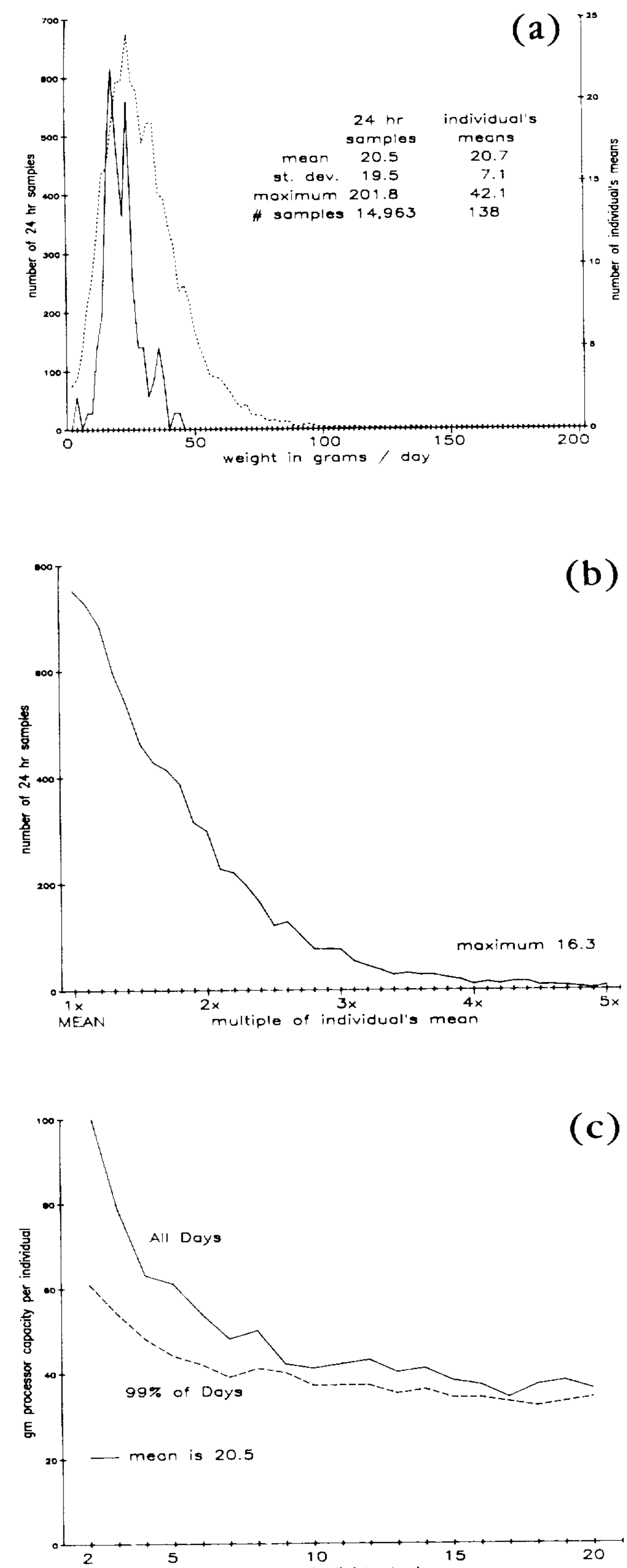


Fig. 2. 24-hour dry stool samples. **(a)** Dashed line is 24-hour samples, solid line is means of individuals. **(b)** Distribution of samples represented as a multiple of that individual's mean. The 45% of samples that exceed the mean are shown. **(c)** Required per-person dry stool processing capacity vs. crew size. The mean is included for comparison.

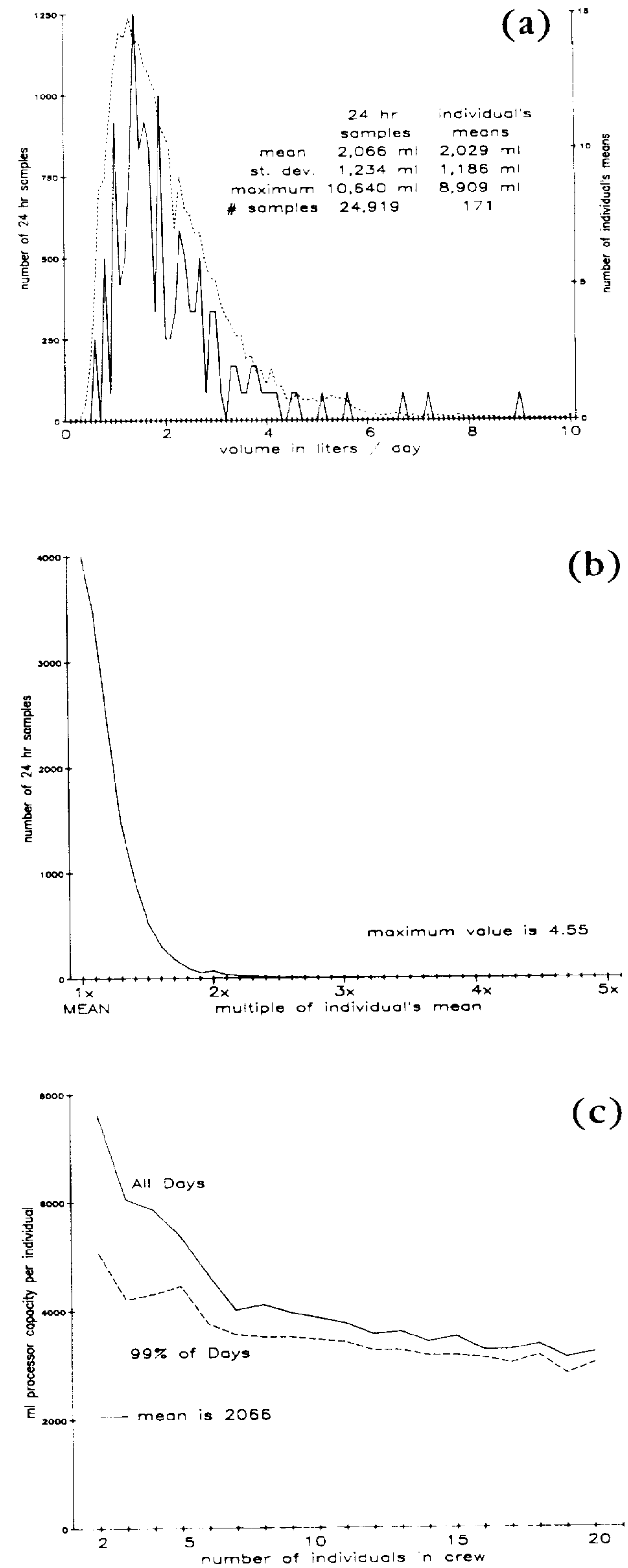


Fig. 3. 24-hour urine samples. **(a)** Dashed line is 24-hour samples, solid line is means of individuals. **(b)** Distribution of samples represented as a multiple of that individual's mean. The 39% of samples that exceed the mean are shown. **(c)** Required per-person urine processing capacity vs. crew size. The mean is included for comparison.

distribution of 24-hour urine samples (dashed line) and the distribution of the 171 individuals' means (solid line). As expected, the distribution of individuals' means is somewhat narrower than that for the daily values. Figure 3b shows the distribution of daily samples as a fraction of the individuals' mean values. Simulation runs for crews of 2 to 20 individuals are presented in Fig. 3c.

Variation in urine output is primarily dependent on fluid intake (78% of the variation in urine volume is explained by variation in fluid consumed in a sample of 11,748 days). The regression (with standard errors) for 24-hour urine samples against fluid consumed is

$$\text{ml urine} = -683\ (\text{SE } 14) + 0.800\ (\text{SE } 0.004) \times \text{ml fluid consumed.}$$

Though many of the subjects in our sample were of college age, no beer drinking occurred during the studies, thus avoiding one factor that is known to produce high urine volumes. However, some subjects were normally drinking large quantities of water, and thus producing large quantities of urine. The extreme individual averaged 10,435 ml of drinking water per day over the 2-month study period. It is possible to bring the means of individuals with high values down by limiting their fluid intake. However, we assume that this limitation on people's normal habits is not appropriate.

There is a shift in distribution of body fluids when an individual goes into zero gravity, resulting in the body dumping fluids for the first few days in space (*Leach and Rambaut,* 1977).

No direct measurements were made on these samples for the dry weight of the urine. Urine was analyzed for specific items of interest in each department.

Menstrual Flow

Menstrual flow is quite variable between individuals. A typical value is about 10 g of solids per menstrual period (estimated from an average of 28 ml blood loss per period) (*Hallberg and Nilsson,* 1964, p. 356); that amount would have little impact on waste handling equipment design. However, the menstrual pads and tampons used during a period do add significantly to the load on the solid waste management.

We have data on 1 to 5 menstrual periods for 34 women for a total of 105 menstrual periods. *Umoren and Kies* (1982, p. 719) present information on the number of pads and tampons used during 30 periods. The mean value was 11.8 with a range of 4-35 in 30 sampled periods. Our comparable results are 16.2 with a range of 3-34. The combined 135 sampled periods shown in Fig. 4 averaged 15.2 per period. Our 105 samples showed 28% of the pad and tampons being used on the second day (peak flow) of the period, or an average of 4.5, with the highest number, 10, occurring once, 9 occurring 5 times, and 6 or more occurring 26% of the time.

A mean weight of six brands of tampons gave an average weight of 2.60 g (range 2.24-2.91 g). Three brands of pads were weighed and averaged 10.65 g (range of 10.6-10.7 g). The mean weight of 9 products is 6.4 g for the first item, so there would be a solid material load of 29 g (6.4 × 4.5) from pads and tampons on the second day of a period. We assume that there are 5 g of solids in menstrual flow on the second day of a period.

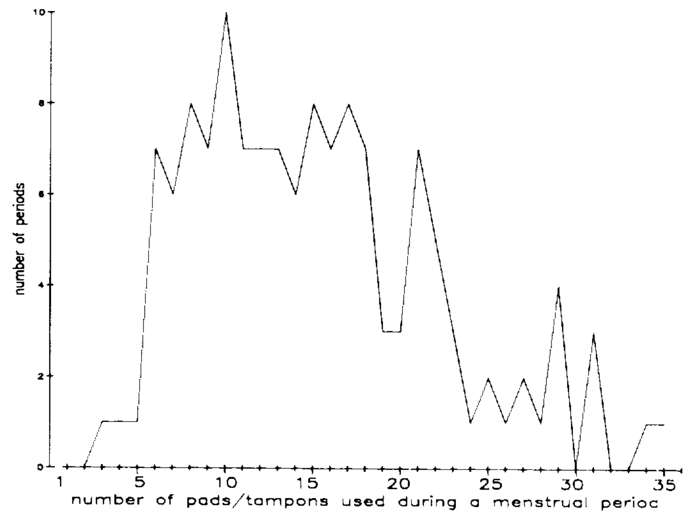


Fig. 4. Distribution of pad and tampon use per menstrual period.

Toilet Paper

Toilet paper adds to the solids load of the waste handling equipment. We have no statistical sample of toilet paper use but estimate about 6 g of toilet paper per movement or per urination by a woman. At 0.855 movements/day, the toilet paper would add 5.1 g, and at 6 urinations/day, toilet paper usage would be increased by 36 g/day/woman.

DISCUSSION

Since the distributions of human waste production are skewed considerably (Figs. 1a, 2a, 3a), it would be unwise to design waste handling equipment around mean values. The crew for a small space facility could easily have a urine or stool output that is signifcantly above the mean value multiplied by that number of individuals.

To monitor the micronutrients over the length of the studies from which our data came, it was necessary to provide food from consistent sources. Consequently, fresh fruit and vegetables were not included in the diet, and the diet is slightly lower than the average American diet in fiber. Quantity of fiber is known to increase the quantity of stool solids. Our values are likely to be slightly lower in quantity of stool solids than the average American diet, but probably similar to space diets before local food growth is developed.

Total Waste Load

Table 1 summarizes our assessment of the waste load design criterion for a crew of eight. Values are given for both 100% coverage and 99% coverage of daily waste production based upon our simulation runs. Separate values are given for the additional sanitary supplies used by women.

The reliability of the values in Table 1 varies. Urine volume, stool water, and stool dry weight are highly reliable, being based on several thousand samples. Urine solids are based on a literature mean value, and we are unable to incorporate statistical variation into this category. Thus, the urine solids value is too small by an

TABLE 1. Suggested daily waste load design level for a crew of eight.

Item	100% level	99% level	Added for women	Daily mean value	Literature
Urine	4,100 ml/person	3,500 ml/person		2,066 ml/person	1,500 ml/person
Stool H_2O	215 ml/person	159 ml/person		75 ml/person	90 ml/person
Total fluid	4,315 ml/person	3,659 ml/person		2,141 ml/person	1,590 ml/person
Crew of 8 total	34,520 ml/day	29,272 ml/day			
Recommended	34.5 liters/day				
Urine solids*	59 g/person	59 g/person			59 g/person
Stool solids	50 g/person	41 g/person		20.5 g/person	32 g/person
Toilet paper	6 g/person	6 g/person	36 g/person†		
Menstrual pads	(37) g/person‡		29 g/person§		
Menstrual flow			5 g/person		
Total solids	115 g/person	106 g/person	70 g/person		91 g/person
Total (50% women)	154 g/person**	145 g/person**			
Crew of 8, total	1,232 g/day	1,160 g/day			
Recommended	1.25 kg/day				

* Urine solids probably vary less than fluid volume. Lacking data we assumed no variation.
† Assumed 6 urinations per day.
‡ Assumed 6 pads/tampons, the 75%ile level.
§ Average of 4.5 pads/tampons times 6.4 g each.
** The weight added for women is $(36 + 37 + 5) \times 0.5 = 39$ g.

Literature values from *Schubert et al.* (1985), *Slavin et al.* (1986), and *Nitta et al.* (1985).

unknown factor. Toilet paper weight may be unreliable, being based upon one brand and an estimate of usage amounts. Menstrual pad and tampon usage is based on a modest sample, 135 periods, with distribution during the period based on 105 periods. Variation in weight between brands of pads and tampons (seven tested) is considerable as well, so the peak flow day weight load is only modestly reliable. However, other studies (*Schubert et al.,* 1985; *Slavin et al.,* 1986) have ignored menstrual supplies entirely, which is inappropriate. Reliability of toilet paper usage by women after urination is low.

This work was done with the intent of obtaining parameters for the design of waste handling facilities for a space facility. In the near future all such systems will be designed for relatively small crews, and statistical variation between individuals is always an issue when dealing with small populations. If a system is designed to handle three individuals, it is likely that a proportion of the possible three-person crews would generate waste loads that are higher than the average of a population, especially when individuals randomly selected for the crew are from a population that has a highly skewed distribution. As the number of individuals to be handled by a system grows, the impact of extreme individuals diminishes. However, as long as small crew sizes are being considered, the design criterion should exceed the population mean by a substantial margin.

We attempted with our computer simulation runs to determine if it was worthwhile building in surge capacity to deal with variations. We concluded that surge capacity would not be helpful because relatively large surge capacity would be required for small decreases in capacity. Surge capacity utilization showed up primarily with the extreme crew rather than with the extreme days for many crews. Since we did not feel that it was appropriate, or likely, to select crew members based upon the individual's physiological and/or behavioral characteristics in these areas we decided to recommend building adequate capacity to process wastes produced by crews with the largest waste production loads.

We did not simulate pad and tampon usage during menstrual periods. Though the average pad and tampon usage on the second day of the menstrual period is 4.5 units, we based our design criterion on 6 units; the 75-percentile level. It has been suggested that menstrual periods of women in close proximity have a tendency to become synchronous. Our design criterion allows for this to happen in the very confined quarters of space habitats. Since this is so obviously grouped in time, it might be reasonable to design temporary storage for this waste; however, though peak menstrual pad and tampon usage and flow occurs only one day a month, we recommend that equipment should be designed to handle this known load.

Emesis (vomit) values are not included in the design estimate because they are assumed to substitute for other items that would be proportionally reduced.

For a crew of eight, we recommend designing for a fluid load of 4315 ml/person/day (34.5 liters for the crew). The average 2141 ml/person/day is likely to be exceeded by a substantial portion of crews.

Our recommended solids waste load design criterion is at least 154 g/person/day (1.25 kg for the crew of eight) for a mixed crew of men and women. The value should be slightly higher than this, but we lack data to show the statistical variation in urine solids.

Table 1 includes values from some recent studies of closed life support systems (*Schubert et al.,* 1985, p. 30; *Slavin et al.,* 1986, p. 14; *Nitta et al.,* 1985, p. 205), and shows some important differences between these studies and our own. Most importantly, we have given considerable emphasis to the wide variation within the human population, while the other studies did not. We do

not believe crews should be selected on the basis of this physiological characteristic. Our mean urine volume is one-third higher than values used in the other studies. Restricting fluid intake reduces urine output, but, again, we believe drinking water should not be limited. Our inclusion of sanitary supplies (toilet paper and pads and tampons) increases the solid waste load by a third. This material was not included in the studies cited.

SUMMARY

We recommend that a design for waste handling systems of a space facility be such that it will permit selection of the crew without consideration of the individual's level of waste production. We have examined the distribution of urine and stool wastes from a sample of 25,000 days and find the data highly skewed. Information is presented to permit estimates of design criteria for crews of 2 to 20 individuals. We suggest design for a crew of 8 to be 34.5 liters per day (4315 ml/person/day) for urine and stool water and a little more than 1.25 kg per day (154 g/person/day) of human waste solids and sanitary supplies.

REFERENCES

Hallberg L. and Nilsson L. (1964) Constancy of individual menstrual blood loss. *Acta Obst. Gynec. Scandinav., 43,* 352-360.

Leach C. and Ranbaut P. (1977) Biochemical responses of the Skylab crewman: An overview. In *Biomedical Results from Skylab* (R. Johnston and L. Dietlein, eds.,) pp. 204-216. NASA, Washington, DC.

Nitta K., Ashida A., Mitani K., Ebara K., and Yamada A. (1985) Water recycling system using thermoperevaporation method. In *CELSS '85 Workshop* (R. MacElroy et al., eds.), pp. 201-225. NASA TM 88215. NASA Ames Research Center, Moffett Field, California.

Schubert F. H., Wynveen R. A., and Quattrone P. D. (1985) Advanced regenerative environmental control and life support systems; air and water regeneration. In *Controlled Ecological Life Support Systems* (R. D. MacElroy, ed.), pp. 29-38. NASA CP-2378. NASA Ames Research Center, Moffett Field, California.

Slavin T., Liening F., Oleson M., and Olson R. L. (1986) *Controlled Ecological Life Support Systems (CELSS) Physiochemical Waste Management Systems Evaluation.* NASA Contractor Report 177422. NASA Ames Research Center, Moffett Field, California.

Tucker D., Sandstead H., Logan G. Jr., Klevay L., Mahalko J., Johnson L., Inman L., and Inglett G. (1981) Dietary fiber and personality factors as determinants of stool output. *Gastroenterology, 81,* 879-883.

Umoren J. and Kies C. (1982) Menstrual blood losses of iron, zinc, copper, and magnesium in adult female subjects. *Nutr. Rep. Int., 26,* 717-726.

BONE LOSS AND HUMAN ADAPTATION TO LUNAR GRAVITY

N93-14002

T. S. Keller and A. M. Strauss

Department of Mechanical Engineering
Vanderbilt University
Nashville TN 37235

Long-duration space missions and establishment of permanently manned bases on the Moon and Mars are currently being planned. The weightless environment of space and the low-gravity environments of the Moon and Mars pose an unknown challenge to human habitability and survivability. Of particular concern in the medical research community today is the effect of less than Earth gravity on the human skeleton, since the limits, if any, of human endurance in low-gravity environments are unknown. This paper provides theoretical predictions on bone loss and skeletal adaptation to lunar and other nonterrestrial-gravity environments based upon the experimentally derived relationship, density ≈ (mass × gravity)$^{1/8}$. The predictions are compared to skeletal changes reported during bed rest, immobilization, centrifugation, and spaceflight. Countermeasures to reduce bone losses in fractional gravity are also discussed.

INTRODUCTION

Since the founding of the National Aeronautics and Space Administration (NASA) in 1958, manned spaceflight has been one of our nation's priorities. The scientific and engineering accomplishments by NASA over the past three decades represent some of the greatest technological achievements in human history. Throughout the course of development of manned spaceflight, one of the chief concerns of physicians and life scientists practicing space medicine has been to assure the health and well-being of astronauts and people who will live and work in space and other non-Earth environments.

After 25 years of U.S. and Soviet manned spaceflight experience, a wealth of physiological data has been gathered and studied. Research conducted on animals and humans exposed to the microgravity (as low as 10^{-6}) or "weightless" state in space has provided a better understanding of the physiological changes resulting from weightlessness. Exposure to the space environment has been found to produce changes in nearly every physiological system, but, in general, humans can acclimate well to weightlessness. Several biomedical problems have been identified, however, that may lead to potentially progressive pathophysiological deterioration, including alterations in vestibular function, cardiovascular deconditioning, hematological imbalances, and bone and mineral imbalances.

Among the most striking findings from space missions and Earth-based simulations of weightlessness is the rapid and continuous loss of bone mineral (*Nicogossian and Parker*, 1982), and alterations in skeletal mass are thought by many scientists to be one of the most serious physiological hazards associated with long-term spaceflight. The major health hazards associated with skeletal bone loss are toxic accumulations of excess mineral in tissues such as the kidney, increased risk of fracture, and potentially irreversible damage to the skeleton. For these reasons, numerous Earth-based and space-based studies are currently being directed toward two complementary goals: (1) elucidating the fundamental mechanisms of skeletal adaptation in altered gravity (or stress) environments and (2) developing practical countermeasures to preserve normal skeletal structure and function.

One often-asked question remains unanswered: How long should an astronaut remain in space? This paper presents theoretical predictions on skeletal adaptation in response to chronic altered weight bearing in a lunar gravity environment. Data from spaceflight, Earth analogs of weightlessness, and centrifugation are compared to theoretically derived predictions. The gravity field question is addressed with the principal aim to define an optimal gravity environment that preserves physiological function and ensures survival.

REVIEW AND THEORY

Spaceflight

In the last two decades, manned space programs conducted by the U.S. and the U.S.S.R. have successfully placed over 319 men and women into near-Earth orbit. Since Soviet cosmonaut Lt. Uri Gagarin's historic single orbit of the Earth lasting 108 minutes (Vostok 1), over 160,000 man hours have been logged in space (as of 1987). Following the first successful Moon landing on July 16, 1969, a total of 600 man hours were logged by U.S. astronauts on the lunar surface, including a record stay of 75 hours on the lunar surface by astronauts Cernan and Schmitt during the Apollo 17 mission (December 7-19, 1972). Shortly thereafter, astronauts Carr, Gibson, and Pogue spent a record-setting 84 days in a millligravity to microgravity environment aboard the Skylab 4 orbital workstation.

Since Skylab, the longest U.S. space mission has been 248 hours aboard the space shuttle STS-9 (Space Transportation System). The Soviets, however, have continued to extend their presence in space and have accumulated 117,000 man hours during 35 Soyuz missions aboard the Salyut and Mir space stations. The Mir station has been constantly manned since February 8, 1987, and on December 29, 1987, 43-year-old Soviet cosmonaut Col. Yuri Romanenko established an Earth-orbit endurance record of 326 days aboard the Mir space station, surpassing the previous Soviet

endurance record by 90 days. Col. Romanenko's 11-month experience attests to the remarkable adaptability of the human body and should provide answers to key questions as well as provide fresh insight into the planning of future spaceflights of even longer duration.

The primary effect of microgravity is the elimination of deformations and mechanical stresses on body tissues that are normally present on the Earth due to its gravitational field. This results in a disordered interaction of afferent mechanoreceptors and the development of sensory conflicts. The major immediate manifestations of microgravity are twofold: a headward redistribution of body fluids and underloading of the musculoskeletal system. The former shifts the center of mass of the body toward the head, triggering nervous, reflex, and hormonal mechanisms of adaptive reactions in order to restore hemodynamic homeostasis. The latter produces changes in movement, coordination, neuromuscular function, metabolic requirements, and intrinsic musculoskeletal structure function relationships, and may reduce the role of the muscular system in hemodynamics as a whole. Exposure to the space environment has been found to produce adaptations in nearly every human physiological system. Some of these adaptations such as motion sickness are self-limiting; others produce progressive changes in different body systems. Among the most striking findings from long-term Skylab and Soyuz Earth-orbit space missions is the rapid and continuous loss of bone mineral, particularly cancellous bone losses, which have been reported to be as high as 0.5% per week in the human calcaneus.

Earth Analogs of Weightlessness

Skylab, Salyut, and Mir Earth-orbit space stations have enabled man to live and work for extended periods in a weightless environment. The long-term physiological effects of spaceflight were originally hypothesized to be similar to the deleterious physiological changes associated with chronic inactivity and immobilization. Consequently, in order to ensure the safety and survivability of the space station crew, ground-based methods were sought that could be used to predict physiological responses to weightlessness and to test and evaluate effective countermeasures to physiological deconditioning. The methods used to simulate weightlessness on Earth have included water immersion, hyperbaric environments, immobilization and restraint of animals, and bed rest, all of which were found to simulate, to a certain degree, some of the many physiological changes associated with spaceflight.

Of the Earth-based techniques, bed rest and immersion techniques result in physiological adaptations closest to the low gravity state. Water immersion produces rapid body fluid redistributions similar to weightlessness, making this method an ideal short-term analog of spaceflight. However, most subjects cannot tolerate long-term exposure to water. As a result, Soviet scientists have developed a "head-out dry immersion" technique, in which subjects are protected from water contact, making prolonged immersion more practical (*Gogolev et al.,* 1986). Bed rest, however, is the most commonly used method to simulate weightlessness. Studies of this type were found to be the most endurable method for chronic exposure (*Sandler and Vernikos,* 1986). Numerous horizontal and "head-down" simulations lasting over six months have also been reported. Head-down or "antiorthostatic" bed rest produces more rapid and pronounced fluid shifts than horizontal bed rest, and more closely reproduces the early physiological effects (orthostatic intolerance) and sensory symptoms (vertigo, nausea, nasal congestion) of weightlessness.

In general, chronic immobilization (bed rest and paralysis) results in a 1% to 2% per week loss in calcaneous cancellous bone mineral content (*Donaldson et al.,* 1970; *Hantman et al.,* 1973; *Hulley et al.,* 1971; *Krolner and Toft,* 1983; *Krolner et al.,* 1983; *Lockwood et al.,* 1973; *Minaire et al.,* 1974, 1981; *Schneider and McDonald,* 1984; *Vignon et al.,* 1970; *Vogel,* 1971). The magnitude of bone loss appears to be unrelated to the underlying course of inactivity (*Arnaud et al.,* 1986). Maximum cancellous bone losses occur after 6-9 months (30-40% loss) and appear to be self-limiting (*Minaire et al.,* 1984). The point at which bone losses become self-limiting will henceforth be referred to as the (Earth) "genetic baseline." The effects of immobilization on cortical bone are much less pronounced, ranging from 0.1% per week (dog humerus) to 0.3% per week (dog radius, ulna) (*Jaworski et al.,* 1980). Differences between cortical and cancellous bone losses have been attributed to the greater surface area of cancellous bone (*Krolner and Toft,* 1983; *Krolner et al.,* 1983), but other factors such as functional differences in weight bearing may also be important. For example, bed-rest studies in which patients have been allowed to ambulate (stand, walk, or cycle) for several hours per day have been effective in reducing cancellous bone losses (*Issekutz et al.,* 1966). Thus, functional weight bearing and postural shifts appear to be important conditioning factors affecting subsequent skeletal reactions.

Adaptation to Increased Activity

In contrast to the hypofunctional skeletal loading conditions of immobilization and spaceflight, hyperfunctional loading conditions in humans have been reported to result in a net increase in bone mass. Clinical studies examining the bone mineral content (BMC) of the playing arm of professional tennis players report increased radial and humeral cortical bone density ranging from 16% (*Jacobson et al.,* 1984) to greater than 30% in comparison to the contralateral arm (*Dalen et al.,* 1985; *Jones et al.,* 1977). Changes in the BMC of top-ranked athletes participating in weight training programs are even more dramatic. *Nilsson and Westlin* (1971) reported an average 50% increase in distal femur BMC in Olympic-class athletes vs. age-matched controls. More recently *Granhed et al.* (1987) reported an average 36% increase (in comparison to age- and weight-matched normal men) in the BMC of the L3 vertebrae of power lifters participating in the 1983 Power Lifting World Championship. They also noted that there was a significant relationship between the total annual weight lifted and the BMC within this group of athletes. Increases in cancellous BMC in distance runner (*Dalen and Olsson,* 1974) and infantry recruits (*Margulies et al.,* 1986) are much less marked, ranging from 5% to 20%.

Several animal experimental strategies have been employed to study the "adaptive" behavior of bone including hypergravitational studies using centrifuges (*Amtmann and Oyama,* 1973, 1976; *Jaekel et al.,* 1977; *Jankovich,* 1971; *Kimura et al.,* 1979; *Smith,* 1977; *Wunder et al.,* 1979), mechanical overloading of limbs by surgical resection (*Carter et al.,* 1980; *Chamay and Tschantz,* 1972; *Goodship et al.,* 1979; *Saville and Smith,* 1966), and externally applied loading techniques (*Burr et al.,* 1984; *Churches and Howlett,* 1982; *Lanyon et al.,* 1982; *O'Connor et al.,* 1987; *Rubin and Lanyon,* 1984, 1985, 1987). These studies have, in general, produced pronounced cortical hypertrophy and increased breaking strength of the same magnitude as those obtained in the clinical studies. Consistent with the moderate changes in BMC associated with distance running, the results of involuntary exercise in rats (*Adams,* 1966; *Donaldson,* 1935; *Kato and

Ishiko, 1966; *Keller and Spengler,* 1989; *Kiiskinen,* 1977; *Lamb et al.,* 1969; *Saville and Whyte,* 1969; *Steinhaus,* 1933; *Tipton et al.,* 1972) have been much less conclusive and significant than the aforementioned adaptational strategies.

Differences in the results of these studies might be the result of differences in the mechanical stimuli (loading type, period, intensity) or to species-specific factors such as animal age, sex, diet, and genetics. In a review article, *Carter* (1982) speculated that, in addition to the above, differences in the results of exercise, hypergravitational, and hyperfunctional studies might be attributed to strain magnitudes, and he hypothesized that the "hypertrophic response to increased bone strain levels is a nonlinear response in mature bone." Subsequent experimental studies demonstrated that mechanical stimuli such as strain rate and strain distribution were critical to the osteoregulatory processes of the skeleton (*Lanyon et al.,* 1982; *O'Connor et al.,* 1982).

More recently *Rubin and Lanyon* (1984, 1985, 1987) and *Lanyon and Rubin* (1984) examined the magnitudes and distributions of surface cortical bone strains required to elicit an osteogenic response using a functionally isolated turkey ulna model. They concluded that the osteoregulatory response of the skeleton was most significant when the mechanical stimuli were dynamic in nature and above or below an "optimal strain environment," increased strains resulting in a positive response, while decreased strains resulted in a negative response. Their results suggest that, regardless of the number of cycles (≥ 20), cortical bone strain magnitudes of 400-1500 microstrain will not result in any net significant change in bone geometry or density (Fig. 1). Activities that exceed the 1500 microstrain threshold will initiate a positive adaptive or "osteogenic" response, whereas prolonged inactivity below 400 microstrain will induce a negative response; the former is analogous to intensive physical activity

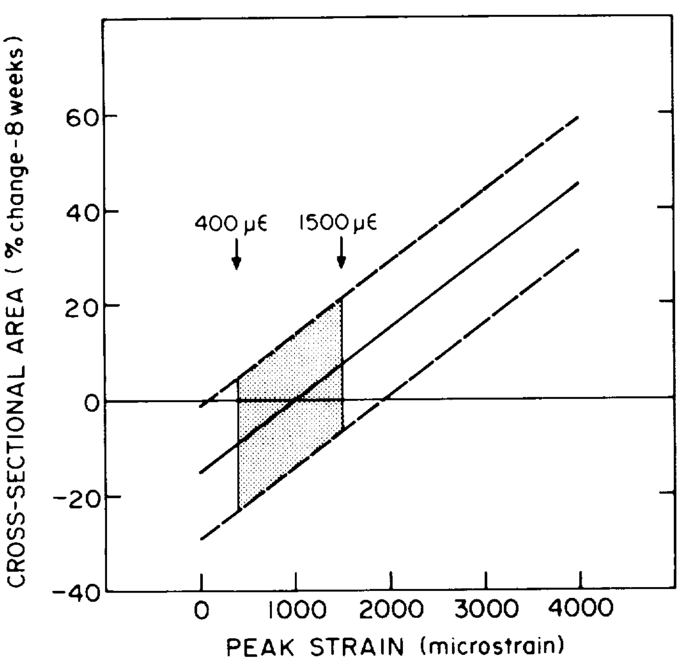


Fig. 1. Adaptational response of the functionally isolated turkey ulna following eight weeks of cyclic loading (100 cycles/day) at peak strains ranging from 0 to 4000 microstrain. Based on data from *Rubin and Lanyon* (1985).

(i.e., sprinting, weight lifting) and the latter is analogous to sedentary activity (bed rest, paralysis, immobilization). In space and nonterrestrial environments such as the Moon and Mars, gravitational forces and forces due to muscle activity are decreased, and both may reduce the subsequent musculoskeletal stimuli below the functional level of strain required to maintain bone mass under normal terrestrial conditions.

Modeling of Skeletal Adaptation

The role of gravity in regulating the functional requirements of the human and animal body has been studied for over a century. *Thompson* (1942) pointed out that "the forms and actions of our bodies are entirely conditioned by the strength of gravity upon this globe.... Gravity not only controls the actions but also influences the forms of all save the least of organisms." Mathematical formulations that characterize the "stress-adaptive" behavior of the skeleton in a feasible manner have yet to be determined. Establishment of permanent Moon and Mars bases and future space exploration, however, necessitate the development of practical empirical solutions concerning skeletal demineralization and effective countermeasures that ensure an adequate level of human performance and, more importantly, survivability in these less-than-Earth-normal gravity environments. In the argument that follows we will describe an experimentally based mathematical formulation that can be used to estimate, in the absence of prophylactic countermeasures, the alterations in skeletal mass associated with microgravity ($10^{-6}\,g$), lunar gravity ($1/6\,g$), and other nonterrestrial environments. The mathematical formulation is based upon the results of dual photon absorptiometry (DPA) measures of lumbar vertebral BMC in a group of world-class power lifters, and the formulation has been generalized to include gravity (g) as a variable. Details of the experimental methods have been previously published by *Granhed et al.* (1987), but a brief description follows.

Eight Swedish world-class power lifters participating in the 1983 World Power Lifting Championships in Göteborg, Sweden, volunteered for the study. Age, height, weight, and L3 vertebral BMC were obtained from each power lifter and from 39 age- and weight-matched "normal" healthy men who served as controls. Dual photon absorptiometry was used to assess the BMC. Detailed weight-training records were obtained from each athlete (including maximum weight lifted and annual weight lifted) and pictures of the athletes during their ground lifts were taken with a high-speed camera. Figure 2 illustrates the way in which the ground lift was performed.

Estimates of the loads on L3 in different positions of the ground lift were calculated using the kinematic model developed by *Schultz and Andersson* (1981) and the ultimate strength of the L3 vertebrae was estimated using experimentally determined relationships for cancellous bone strength vs. density (*Hansson et al.,* 1980, 1987).

The mean BMC value of the power lifters (7.06 ± 0.87 g/cm) was 36% greater than that of the age- and weight-matched controls (5.18 ± 0.88 g/cm). Estimates of the ultimate strength of the L3 vertebrae were 4.1 times greater than the estimated peak L3 loads during the ground lift maneuver. The ratio of ultimate strength *in vivo* load is defined as the safety factor (SF). Long bone SFs have been experimentally determined to lie in the range three to five (*Biewener,* 1982, 1983; *Keller and Spengler,* 1988; *Rubin and Lanyon,* 1982), which is consistent with the mean value of 4.1 obtained for the power lifters.

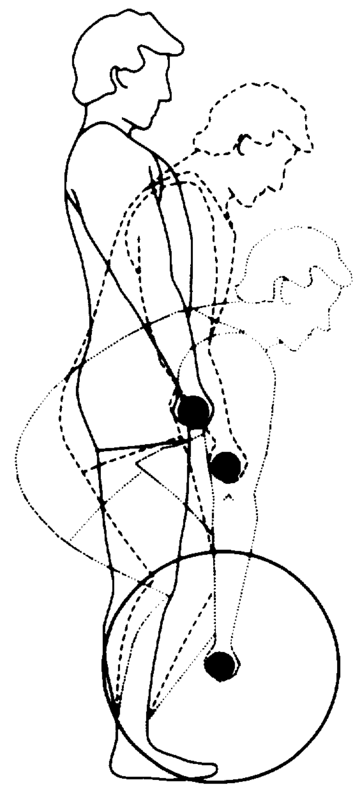


Fig. 2. Schematic representation of the ground lift maneuver. Reprinted from *Granhed et al.* (1987).

Table 1 summarizes the results of the analysis of the forces required to elicit an increase in BMC by increments of 10%. As indicated in Table 1, the change in BMC is highly nonlinear in terms of the mechanical stimulus: More than a thirtyfold increase in total force was required to elicit a 50% increase in BMC. The data can be represented mathematically as

$$BMC \propto [\Sigma F]^{1/8} \quad (1)$$

where ΣF is the total force experienced during weight training by the L3 vertebrae in a one-year period.

Manned spaceflights, missions to the Moon and Mars, and the establishment of lunar and martian bases will take place in gravitational environments where the weight, defined as the force of terrestrial gravitation, experienced by the human or animal body will be reduced. A body of mass m on the Earth (of mass M and radius R_o) experiences a weight

$$F_g = M(GM/R_o^2) = mg \quad (2)$$

where G is a universal constant and g is a constant equal to the acceleration due to the Earth's force of gravity. Simple substitution of equation (2) into equation (1) yields

$$BMC \propto [\Sigma mg]^{1/8} \quad (3)$$

Assuming that bone adapts to reduced forces in a similar manner as increased forces, then one can predict the changes in L3 BMC during, for example, Moon life ($GM/R_o^2 = 1/6\,g$), in terms of

$$BMC \propto 0.799\,[\Sigma mg]^{1/8} \quad (4)$$

where 0.799 represents the BMC fraction retained annually. Similar predictions can be obtained for other non-Earth environments by substituting the appropriate Earth gravity ratio $(GM/R_o^2)/g$. The exponent in equation (3) can also be verified analytically using a "dimensional analysis" (see Appendix).

TABLE 1. Lumbar bone mineral content changes due to hyperactivity.

BMC (g/cm)	Increase (%)	ΣF (kg/yr × 10^6)
5.2	0	1.5
5.7	10	2.9
6.3	20	6.1
6.9	30	12.0
7.6	40	24.7
8.4	50	52.4

Based on the data of *Granhed et al.* (1987).

RESULTS AND DISCUSSION

The effects of adaptation to altered gravitation environments are predicted in Table 2. Equation (4) predicts that under normal activity conditions, a person will experience a 21.1% reduction in L3 BMC per year, or an average weekly loss of 0.41% in a lunar gravity field. In terms of bone strength, this represents a reduction of 0.7% per week (*Hansson et al.,* 1980, 1987). Skeletal adaptation to the lunar gravity field would require roughly 120 weeks for lunar homeostatis (83% strength reduction). Assuming an optimal safety factor for bone of 3 (*Alexander,* 1984), the longest Moon mission for a safe return to Earth would be about 96 weeks (66.6 strength reduction). By Earth standards, microgravity ($\leq 10^{-6}\,g$) would require approximately 5-6 months for skeletal homeostatis (30-40% bone loss), and the skeleton would be at risk for fracture after 35 weeks. In terms of homeostatis in fractional and microgravity environments, it is not known whether these effects would be self-limiting as they appear to be for immobilized patients on Earth. Furthermore, bone losses in cosmonauts exposed to chronic periods of weightlessness (0.5% per week) are much less dramatic than the model predictions, reflecting the fact that cosmonauts generally exercise 2-4 hours per day and wear elastic-corded "penguin" suits up to 16 hours/day. Using a value of -0.5% BMC per week, the model predicts that the longest safe space mission would be about 60 weeks,

TABLE 2. Predicted BMC and strength changes due to altered gravity field.

	Environment g	BMC (%/week)	Strength (%/week)	Stasis (weeks)	SF = 1 (weeks)
Space	$<10^{-6}$	-1.58	-1.86	54	36
Moon	0.17	-0.39	-0.69	120	96
Mars	0.4	-0.22	-0.42	153	159
Earth	1.0	0	0	0	0
Jupiter	2.7	0.25	0.54	314	—

which is slightly greater than the current microgravity endurance record (47 weeks).

The effects of fractional gravity and hypergravity presented in Table 2 are depicted graphically in Fig. 3. Based on ranges of immobilization data (*Donaldson et al.*, 1970; *Hantmann et al.*, 1973; *Hulley et al.*, 1971; *Krolner and Toft*, 1983; *Krolner et al.*, 1983; *Lockwood et al.*, 1973; *Minaire et al.*, 1974, 1981; *Schneider and McDonald*, 1984; *Vignon et al.*, 1970; *Vogel*, 1971) and spaceflight data (*Gazenko et al.*, 1982; *Rambaut and Johnson*, 1979; *Stupakov et al.*, 1984) obtained from the literature, the "1/8 Power Law" of equation (3) suggests that immobilization and spaceflight are comparable to a 10^{-2} to 10^{-3} gravity environment and Moon-Mars gravity environment, respectively. Centrifuge data obtained from dogs exposed to chronic accelerations of 2.5 *g* (*Oyama*, 1975) are in close agreement with the model predictions, but the data obtained from rats (*Amtmann et al.*, 1979; *Oyama and Zeitman*, 1967; *Wunder et al.*, 1979) are more scattered and deviate considerably from the model predictions. The latter may reflect the fact that adult rats do not experience bone internal remodeling. Dog and human bones model and remodel and achieve skeletal adaptations through changes in surface geometry and internal architecture.

The temporal changes in cancellous BMC and strength associated with bed rest and spaceflight along with model predictions for space, Moon, and Mars environments are illustrated in Fig. 4. The model predicts that microgravity and lunar and martian gravitational environments will result in a net 1.6% per week, 0.7% per week, and 0.4% per week loss in BMC, respectively, in the absence of prophylactic measures. Changes in BMC associated with bed rest and immobilization are in close agreement with the predicted losses accompanying microgravity ($\leq 10^{-6} g$). As described earlier, the experimentally measured changes in BMC associated with spaceflight are much less dramatic than the bed-rest data and fall in the range of 0.4% per week to 0.7% per week losses in BMC. The horizontal dashed line corresponding to losses in bone strength of 66.6% in Fig. 4 represents the genetic baseline at which point no further bone loss will occur (Earth-gravity standard). This point (66.6%) also corresponds to the clinical horizon or point at which the skeleton is at an increased risk for fracture (no margin for safety). Note that in a microgravity or fractional-gravity environment, the genetic baseline may not be the same as that for Earth.

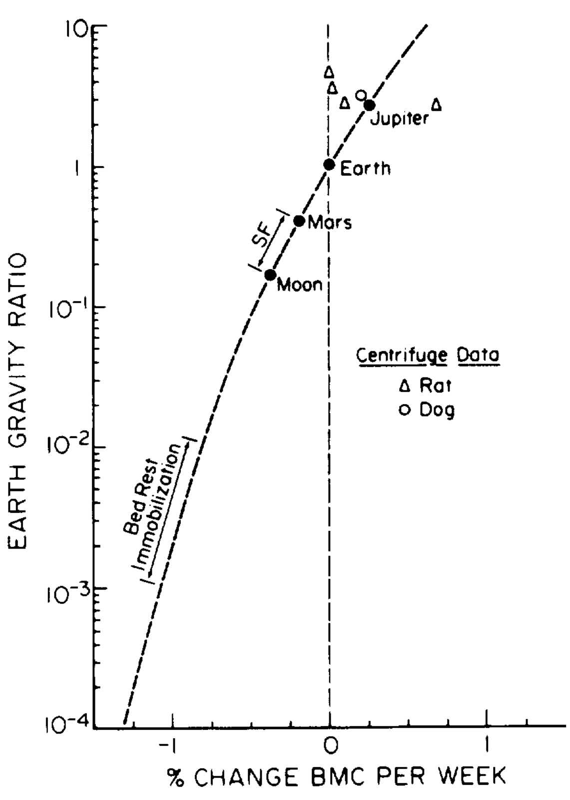


Fig. 3. Log-linear plot of the effects of fractional gravity and hypergravity on the change in BMC based upon the "1/8 Power Law" of equation (3).

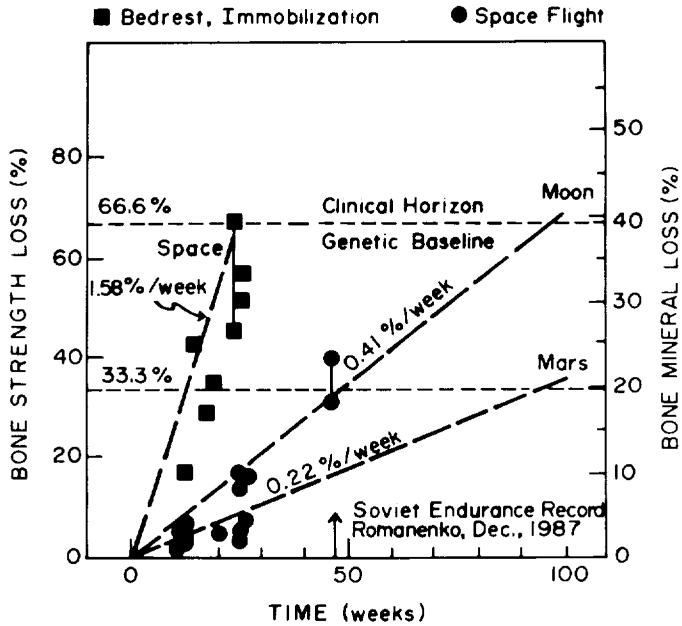


Fig. 4. Temporal changes in bone strength (left ordinate) and bone mineral content (right ordinate) as a function of time (weeks). Experimental data from bed rest (solid squares) and spaceflight (solid circles) are shown (see text for literature citation). The data points connected by bars represent data ranges for which exact values were not available from the literature citation.

In the absence of countermeasures, the results presented in Table 2 and Figs. 3 and 4 provide a preliminary estimate of the long-term effects of microgravity and fractional gravity on the human cancellous skeleton. Although these results are based upon clinical observations of bone changes in lumbar vertebrae, reasonable estimates of the changes in other skeletal sites, such as cortical and cancellous bone in the appendicular skeleton, can be obtained provided suitable adjustments are made. For example, our results would overestimate (nearly threefold) changes in diaphyseal regions of long bones where the rate of bone loss appears to be the lowest in the skeleton. Additional factors such as histories of activity, age, and body weight may also affect the precision of these estimates.

Application of the empirical formulae presented in this paper makes an important, but currently inadequately supported, assumption that results obtained for an osteogenic or positive skeletal adaptive response can be extrapolated to negative skeletal adaptations associated with disuse and fractional-gravity environments. Preliminary support for the assumption has been provided, however, by the experimental studies of *Rubin and Lanyon*

(1984, 1985, 1987), which suggest that the adaptive behavior of bone corresponding to hypo- and hyperactivity are linear functions of bone strain. Data obtained from future fractional-gravity experiments may provide additional support for this assumption.

The theoretical results presented in this paper provide insight into the limits (if any) of human performance and survivability in non-Earth environments. This is an issue of major importance in terms of extended human presence in future orbiting space stations, during long-term space exploration, and on permanently manned Moon and Mars bases. In a lunar gravitational environment ($1/6\,g$), bone strength losses of 0.7% per week would limit human presence on the Moon to about 100 weeks, at which point a weakened skeletal structure could create serious hazards to crew health during the stresses of reentry and return to terrestrial gravitation. Similarly, more than three years could be spent in Mars environment ($3/8\,g$) before a weakened skeleton would be health threatening. This would be equivalent to a period of about 35 weeks in a microgravity environment ($10^{-6}\,g$). The latter is consistent with the results of bed-rest and immobilization data but appears to be grossly underestimated in terms of data obtained from astronauts and cosmonauts chronically exposed to microgravity. Physiological manifestations intrinsic to the absence of a gravitation field such as nervous, hormonal, and hemodynamic factors and/or countermeasures employed during space missions may be responsible for this apparent inconsistency.

On the basis of changes in skeletal mass observed during increased activity, and in lieu of the recent 11-month endurance record established by Soviet cosmonaut Romanenko, we might predict that humans can function and survive indefinitely in a microgravity or fractional-gravity environment provided that adequate countermeasures are taken. Preliminary reports by Soviet space officials that appears in the December 29, 1987, issue of the New York *Times* indicate that Col. Romanenko was in good health following his return to Earth. In addition to a rigorous work schedule, Soviet cosmonauts exercise two hours a day on a stationary bicyle and a treadmill, and they wear suits fitted with elastic bands ("penguin" suits) that provide resistance to movement and thus aid muscular conditioning. While countermeasures of this nature appear adequate for relatively long space missions, the results of this study suggest that more time- and energy-effective exercise measures might include, for example, anaerobic weight lifting.

Alternatively, artificial gravity may be sufficient to preserve musculoskeletal conditioning within safe limits. Our results suggest that a $3/8$-g field should preserve skeletal strength above the fracture risk level for over three years. One scenario for a manned mission to Mars being considered by NASA is an "all-up" type of mission, which would require a 36-month round trip. In this type of mission the crew, equipment, and supplies are transported together in one vehicle. Such a mission would be nearly three times as long as the current human microgravity endurance record. An artificial gravity field of $3/8\,g$ should be sufficient to preserve muscoloskeletal integrity for the round trip to Mars and, in addition, would enable the crew to acclimate to the martian gravitational field. Artificial gravity, however, may not be the most effective solution as problems associated with gravity gradients, vehicle design, and energy expenditure may be prohibitive. Exercise in conjunction with other countermeasures, such as as osteogenic drug therapy, may be more practical. In addition, problems associated with breakdown of the immune and cardiovascular systems must also be considered.

CONCLUSION

This study's finding of a close correlation between skeletal adaptation and activity provides the framework for the development of future studies that will address the question of human survival and habitability in space and on the Moon or Mars. Our results predict that, in the absence of suitable countermeasures, there are limits to the ability of humans to function in space for extended periods and then return to Earth-normal gravity. Based upon the results of previous clinical investigations of the osteogenic response of bone during increased activity, we believe that rigorous activity such as weight training and sprinting are more effective than more sedentary and less intensive activities such as bicycling and running exercises. In addition, a $3/8$-g artifical gravity environment should sustain skeletal function in space at a level suitable for a return to Earth for periods of greater than three years. Fractional-gravity studies and studies of osteogenic-inducing agents also deserve attention.

APPENDIX

Dimensional Analysis

Consider the parameters mass (M), gravity (g), density (ρ), and modulus (E), which, with the exception of E, are representative of the measured quantities comprising the power lifters data. The above parameters are related to the fundamental quantities mass (M), length (L), and time (T) as follows (*Keller,* 1988)

	(k_1) ρ	(k_2) M	(k_3) g	(k_4) E
M	1	1	0	1
L	-3	0	1	-1
T	0	0	-2	-2

The power coefficients (k_i) are thus related by the following equations

$$k_1 + k_2 + k_3 = 0 \tag{A1}$$

$$-3k_1 + k_3 - k_1 = 0 \tag{A2}$$

$$-2k_3 - 2k_4 = 0 \tag{A3}$$

Note that the number of dimensionless groups (DG) equals the number of parameters minus the matrix rank, namely DG = 4 - 3 = 1. There are three equations and four unknowns. If, however, we arbitrarily assign a power coefficient of 1 to the coefficient k_1, one can show that the coefficients k_2, k_3, and k_4 become

	(k_1) ρ	(k_2) M	(k_3) g	(k_4) E
π	1	-1/2	-1/3	-3/2

where the K_i represent power coefficients in the dimensionless expression

$$\pi = \rho[M^{1/2}E^{3/2}g^{3/2}] \quad (A4)$$

In the case of the power lifters, E is an experimentally indeterminant quantity, but is related to bone density as $E \propto \rho^3$ (*Carter and Hayes*, 1976). Substituting the above into equation (A4) and simplifying yields

$$\rho \propto M^{1/7}g^{3/7} \quad (A5)$$

$$\rho \propto (Mg^3)^{1/7} \quad (A6)$$

On Earth g is a constant, and equation (6) reduces to

$$\rho \propto M^{1/7} \quad (A7)$$

The exponent 1/7 in equation (A7) was found experimentally to be 1/8 using the density and weight-lifted data obtained for the power lifters.

Acknowledgments. The authors would like to thank H. Granhed and T. Hansson of the University of Göteborg for their cooperation and for permitting the power lifter data to be utilized in this study.

REFERENCES

Adams J. E. (1966) Little league shoulder. Osteochondrosis of the proximal humeral epiphysis in boy baseball pitchers. *Calif. Med., 105,* 22-25.

Alexander R. McN. (1984) Optimum strengths for bones liable to fatigue and accidental fracture. *J. Theor. Biol., 109,* 621-636.

Amtmann E. and Oyama J. (1973) Changes in functional construction of bone in rats under conditions of simulated increased gravity. *Anat. Entwicklungsgesch., 139,* 307-318.

Amtmann E. and Oyama J. (1976) Effects of chronic centrifugation on the structural development of the musculo-skeletal system of the rat. *Anat. Embryol., 149,* 47-70.

Amtmann E., Kimura T., Oyama J., Doden E., and Potulski M. (1979) Maximum likelihood factor analysis of the effects of chronic centrifugation on the structural development of the musculoskeletal system of the rat. *Anat. Embryol., 156,* 89-101.

Arnaud S. B., Schneider V. S., and Morey-Holton E. (1986) Effects of inactivity on bone and calcium metabolism. In *Inactivity: Physiological Effects* (H. Sandler and J. Vernikos, eds.), pp. 49-76. Academic, Orlando.

Biewener A. A. (1982) Bone strength in small mammals and bipedal birds: Do safety factors change with body size? *J. Exp. Biol., 98,* 289-301.

Biewener A. A. (1983) Locomotory stresses in the limb bones of two small mammals: The ground squirrel and chipmunk. *J. Exp. Biol., 103,* 131-154.

Burr D. B., Martin R. B., and Lefever S. (1984) The prevention of disuse osteoporosis in sedentary rabbits. *Trans. ORS, 9,* 146.

Carter D. R. (1982) The relationship between *in vivo* strains and cortical bone remodeling. *Crit. Rev. Biomed. Eng., 8,* 1-28.

Carter D. R. and Hayes W. C. (1976) Bone compressive strength: The influence of density and strain rate. *Science, 194,* 1174-1176.

Carter D. R., Smith D. J., Spengler D. M., Daly C. H., and Frankel V. H. (1980) Measurement and analysis of *in vivo* bone strains on the canine radius and ulna. *J. Biomechanics, 13,* 27-38.

Chamay A. and Tschantz P. (1972) Mechanical influences in bone remodeling. Experimental research on Wolff's law. *J. Biomechanics, 5,* 173-180.

Churches A. E. and Howlett C. R. (1982) Functional adaptation of bone in response to sinusoidally varying controlled compressive loading of the ovine metacarpus. *Clin. Orthop. Relat. Res., 168,* 265-280.

Dalen N. and Olsson K. E. (1974) Bone mineral content and physical activity. *Acta Orthop. Scand., 45,* 170-174.

Dalen N., Laftman P., Ohlsen H., and Stromberg L. (1985) The effect of athletic activity on the bone mass in human diaphyseal bone. *Orthopedics, 8,* 1139-1141.

Donaldson C. L., Hulley S. B., Vogel J. M., Hattner R. S., Bayers J. H., and McMillan D. E. (1970) Effect of prolonged bed rest on bone mineral. *Metabolism, 19,* 1071-1084.

Donaldson H. H. (1935) Summary of data for the effects of exercise on the organ weights of the albino rat: Comparison with similar data from the dog. *Am. J. Anat., 56,* 57-70.

Gazenko O. G., Genin A. M., and Egoro A. D. (1982) Major medical results of the Salyut-6-Soyuz 185-day space flight. In *Space: Mankind's Fourth Environment XXXII International Astronautical Congress, Rome 1981,* pp. 275-293. Pergamon, Oxford.

Gogolev K. I., Aleksandrova Ye. A., and Shul'zhenko Ye. B. (1980) Comparative evaluation of changes in the human body during orthostatic (head down) hypokinesia and immersion. *Fiziol. Chel., 6,* 978-983.

Goodship A. E., Lanyon L. E., and McFie H. (1979) Functional adaptation of bone to increases stress. *J. Bone Joint Surg., 61A,* 539-546.

Granhed H., Jonson R., and Hansson T. (1987) The loads on the lumbar spine during extreme weight lifting. *Spine, 12,* 246-249.

Hansson T., Roos B., and Nachemson A. (1980) The bone mineral content and ultimate compressive strength of lumbar vertebrae. *Spine, 5,* 46-55.

Hansson T. H., Keller T. S., and M. M. Panjabi (1987) A study of the compressive properties of lumbar vertebral trabeculae: Effects of tissue characteristics. *Spine, 12,* 56-62.

Hantmann D. A., Vogel J. M., Donaldson C. L., Friedman R., Goldsmith R. S., and Hulley S. B. (1973) Attempts to prevent disuse osteoporosis by treatment with calcitonin, longitudinal compression and supplementary calcium and phosphate. *J. Clin. Endocrin. Metab., 36,* 845-858.

Hulley S. B., Vogel J. M., Donaldson C. L., Bayers J. H., Friedman R. J., and Rosen S. N. (1971) The effect of supplemental oral phosphate on the bone mineral changes during prolonged bed rest. *J. Clin. Invest., 50,* 2506-2518.

Issekutz B., Blizzard J., Birkhead N., and Rodahl K. (1966) Effect of prolonged bed rest on urinary calcium output. *J. Appl. Physiol., 21,* 1013-1020.

Jacobson P. C., Beaver W., Grubb S. A., Taft T. N., and Talmage R. V. (1984) Bone density in women: College athletes and older athletic women. *J. Orthop. Res., 2,* 328-332.

Jaekel E., Amtmann E., and Oyama J. (1977) Effect of chronic centrifugation on bone density of the rat. *Anat. Embryol., 151,* 223-232.

Jankovich J. P. (1971) *Structural Development of Bone in the Rat Under Earth Gravity, Simulated Weightlessness, Hypergravity and Mechanical Vibration.* NASA CR-1823. 140 pp.

Jaworski Z. F. G., Liskova-Kiar M., and Uhthoff H. K. (1980) Effects of long-term immobilisation on the pattern of bone loss in older dogs. *J. Bone Joint Surg., 62B,* 104-110.

Jones H. H., Priest J. D., Hayes W. C., Tichenor C. C., and Nagel D. A. (1977) Humeral hypertrophy in response to exercise. *J. Bone Joint Surg., 59A,* 204-208.

Kato S. and Ishiko T. (1966) Obstructed growth in children's bones due to excessive labor in remote corners. *Proc. Int. Congr. Sport Sci.,* p. 476.

Keller T. S. (1988) *Functional Adaptation of Bone During Growth and Altered Activity.* Ph.D. thesis, Vanderbilt Univ., Nashville, Tennessee. 435 pp.

Keller T. S. and Spengler D. M. (1989) Regulation of bone stress and strain in the immature and mature rat femur. *J. Biomechanics, 22,* 1115-1127.

Kiiskinen A. (1977) Physical training and connective tissue in young mice—Physical properties of Achilles tendons and long bones. *Growth, 41,* 123-137.

Kimura T., Amtmann E., Doden E., and Oyama J. (1979) Compressive strength of the rat femur as influenced by hypergravity. *J. Biomechanics, 12,* 361-365.

Krolner B. and Toft B. (1983) Vertebral bone loss: An unheeded side effect of therapeutic bed rest. *Clin. Sci., 64,* 537-540.

Krolner B., Toft B., Nielsen S. P., and Tondevold E. (1983) Physical exercise as prophylaxis against involutional vertebral bone loss: A controlled trial. *Clin. Sci., 64,* 541-546.

Lamb D. R., Van Huss W. D., Carrow R. E., Heusner W. W., Weber J. C., and Kertzer R. (1969) Effects of prepubertal physical training on growth, voluntary exercise, cholesterol and basal metabolism in rats. *Res. Q., 40,* 123-133.

Lanyon L. E. and Rubin C. T. (1984) Static vs. dynamic loads as an influence on bone remodeling. *J. Biomechanics, 17,* 897-905.

Lanyon L. E., Goodship A. E., Pye C. J., and MacFie J. H. (1982) Mechanically adaptive bone remodeling. *J. Biomechanics, 15,* 141-154.

Lockwood D. R., Lammert J. E., Vogel J. M., and Hulley S. B. (1973) Bone mineral loss during bed rest. In *Clinical Aspects of Metabolic Bone Disease* (B. Frame, A. M. Parfitt, and H. Duncan, eds.), pp. 261-265. Excerpta Medica, Amsterdam.

Margulies J. Y., Simkin A., Leichter I., Bivas A., Steinberg R., Giladi M., Stein M., Kashtan H., and Milgrom C. (1986) Effect of intense physical activity on the bone-mineral content in the lower limbs of young adults. *J. Bone Joint Surg., 68A,* 1090-1093.

Minaire P., Berard E., Meunier P. J., Edouard C., Goedert G., and Pilonchery G. (1981) Effects of disodium dichloromethylene diphosphanate on bone loss in paraplegic patients. *J. Clin. Invest., 68,* 1086-1092.

Minaire P., Edouard C., Arlot M., and Meunier P. J. (1984) Marrow changes in paraplegic patients. *Calcif. Tiss. Int., 36,* 338-340.

Minaire P., Meunier P., Edouard C., Bernard J., Courpron P., and Bourret J. (1974) Quantitative histological data on disuse osteoporosis. Comparison with biological data. *Calc. Tiss. Res., 17,* 57-73.

Nilsson B. E. and Westlin N. E. (1971) Bone density in athletes. *Clin. Orthop. Relat. Res., 77,* 179-182.

Nocogossian A. E. and Parker J. F. Jr. (1982) *Space Physiology and Medicine.* U.S. Govt. Printing Office, Washington, DC. 324 pp.

O'Connor J. A., Lanyon L. E., and MacFie H. (1982) The influence of strain rate on adaptive bone remodeling. *J. Biomechanics, 15,* 767-781.

Oyama J. (1975) Response and adaptation of beagle dogs to hyperactivity. In *COSPAR: Life Sciences and Space Research XIII* (P. H. A. Sneath, ed.), pp. 2-17. Akademie-Verlag, Berlin.

Oyama J. and Zeitman B. (1967) Tissue composition of rats exposed to chronic centrifugation. *Am. J. Physiol., 213,* 1305-1310.

Rambaut P. C. and Johnson R. S. (1979) Prolonged weightlessness and calcium loss in man. *Acta Astronaut., 6,* 1113-1122.

Rubin C. T. and Lanyon L. E. (1982) Limb mechanics as a function of speed and gait: A study of functional strains in the radius and tibia of horse and dog. *J. Exp. Biol., 101,* 187-211.

Rubin C. T. and Lanyon L. E. (1984) Regulation of bone formation by applied dynamic loads. *J. Bone Joint Surg., 66A,* 397-402.

Rubin C. T. and Lanyon L. E. (1985) Regulation of bone mass by mechanical strain magnitude. *Calcif. Tiss. Int., 37,* 411-417.

Rubin C. T. and Lanyon L. E. (1987) Osteoregulatory nature of mechanical stimuli: Function as a determinant for adaptive remodeling in bone. *J. Orthop. Res., 5,* 300-310.

Sandler H. and Vernikos J., eds. (1986) *Inactivity: Physiological Effects.* Academic, Orlando. 205 pp.

Saville P. D. and Smith R. (1966) Bone density, breaking force and leg muscle mass as functions of weight in bipedal rats. *Am. J. Phys. Anthropol., 25,* 35-40.

Saville P. D. and Whyte M. P. (1969) Muscle and bone hypertrophy. Positive effect of running exercise in the rat. *Clin. Orthop. Relat. Res., 65,* 81-88.

Schneider V. S. and McDonald J. (1984) Skeletal calcium homeostatis and countermeasures to prevent disuse osteoporosis. *Calcif. Tiss. Int., 36,* S151-S154.

Schultz A. B. and Anderson G. B. J. (1981) Analysis of loads on the lumbar spine. *Spine, 6,* 76-82.

Smith S. D. (1977) Femoral development in chronically centrifuged rats. *Aviat. Space Environ. Med., 48,* 828-835.

Steinhaus A. H. (1933) Chronic effects of exercise. *Physiol. Rev., 13,* 103-147.

Stupakov G. P., Kazeykin V. S., Koslovskiy A. P., and Korolev V. V. (1984) Evaluation of changes in human axial skeletal bone structures during long-term spaceflights. *Space Biol. Aerospace Med., 18,* 42-47.

Thompson D'Arcy W. (1942) *On Growth and Form.* Cambridge Univ., New York. 1116 pp.

Tipton C. M., Mathes R. D., and Maynard J. A. (1972) Influence of chronic exercise on rat bones. *Med. Sci. Sports, 4,* 55.

Vignon G., Meunier P., Pansu D., Bernard J., Chapuy P., Edouard C., and Courpron P. (1970) Enquet clinique et anatomique sur l'etiopathogenie de l'osteoporose senile. *Rev. Rhum. Mal. Osteo-Articulaires, 37,* 615-627.

Vogel J. M. (1971) Changes in bone mineral content of the Os Calcis induced by prolonged bed rest. In *Hypogravic and Hypodynamic Environments* (R. H. Murray and M. McCally, eds.), pp. 261-269. NASA Scientific and Technical Information Office, Washington, DC.

Wunder C. C., Welch R. C., and Cook K. M. (1979) Femur strength as influenced by growth, bone-length and gravity with the male rat. *J. Biomechanics, 12,* 501-507.

7 / *Operations and Infrastructure on the Lunar Surface*

CONCEPTUAL DESIGN OF A LUNAR BASE THERMAL CONTROL SYSTEM

Lisa C. Simonsen

NASA Langley Research Center
Hampton VA 23665-5225

Marc J. DeBarro

Rockwell International
12214 Lakewood Blvd.
Downey CA 90241

Jeffery T. Farmer

NASA Langley Research Center
Hampton VA 23665-5225

Space station and alternate thermal control technologies were evaluated for lunar base applications. The space station technologies consisted of single-phase, pumped water loops for sensible and latent heat removal from the cabin internal environment and two-phase ammonia loops for the transportation and rejection of these heat loads to the external environment. Alternate technologies were identified for those areas where space station technologies proved to be incompatible with the lunar environment. Areas were also identified where lunar resources could enhance the thermal control system. The internal acquisition subsystem essentially remained the same, while modifications were needed for the transport and rejection subsystems because of the extreme temperature variations on the lunar surface. The alternate technologies examined to accommodate the high daytime temperatures incorporated lunar surface insulating blankets, heat pump system, shading, and lunar soil. Other heat management techniques, such as louvers, were examined to prevent the radiators from freezing. The impact of the geographic location of the lunar base and the orientation of the radiators was also examined. A baseline design was generated that included weight, power, and volume estimates.

INTRODUCTION

Permanent manned presence on the Moon has been identified by the National Commission on Space as one of the bold new initiatives beyond the space station to explore and settle the solar system (*Ride,* 1987). Accordingly, a joint systems study between NASA Langley Research Center (LaRC) and NASA Johnson Space Center (JSC) was conducted to aid in determining the appropriate systems required by man to survive for extended durations on the lunar surface. The thermal control system (TCS) was identified as a key element for the efficient operation of the lunar base.

This paper discusses the major elements of a conceptual design of a lunar base thermal control system. Both passive and active options were considered for temperature control in the manned sections of the base. The extreme variations of the lunar surface temperature in the lower latitudinal regions were addressed in the conceptual design. Space station thermal control technology was used as the baseline in developing the thermal control design.

LIST OF SYMBOLS

H	Height (m)
h	Heat Transfer Coefficient ($W/m^2{\cdot}K$)
k	Thermal Conductivity (W/m-K)
P	Pressure (kPa)
Q	Heat (kW)
q	Heat Flux (W/m^2)
r	Radius (m)
T	Temperature (K)
α	Absorptivity
ϵ	Emissivity
γ	Angle of Incidence of the Solar Flux on the Radiator (Deg.)
η_c	Isentropic Efficiency
ϕ	Latitude (Deg.)
σ	Stefan-Boltzmann Constant
Θ	Angle Sun is Above Lunar Horizon (Deg.)

subscripts:

Al	Aluminum
N	Normal
rad	Radiator
reg	Regolith
sink	Environmental Sink
1	Inner Module Wall
2	Surface of MLI
3	Inner Surface of Aluminum Structure
4	Outer Surface of Aluminum Structure
5	Lunar Surface

APPROACH

The configuration of the lunar base habitat was designed to meet requirements established by JSC. The impact of the lunar environment on the habitat and the proposed activities in the facility were evaluated to determine design specifications for the thermal control system.

A baseline configuration for the thermal control system was developed using the current space station thermal control technologies. The acquisition technology for the internal heat

loads in the space station consists of single-phase, pumped water loops that operate at temperatures of 2°C and 21°C for sensible and latent heat removal. A two-phase ammonia loop transports the heat from the modules to a series of individual ammonia heat pipe radiators (*NASA*, 1984). Passive thermal control was assumed to consist primarily of standard multilayer insulation.

If the space station technology proved inadequate for lunar application, it was either modified to accommodate the lunar environment or replaced by an alternate technology. Using this approach, the thermal control systems for the first phases of a permanent lunar base were established using as many known and tested technologies as applicable. Thermal control system summaries for the habitable areas of the lunar base were then generated using information available on the technologies selected.

LUNAR BASE DESCRIPTION

A lunar base functional analysis received from JSC was used to determine the habitat and laboratory facilities required to sustain base operations. Two phases of the lunar base were addressed, an initial phase and a growth phase. The initial phase will support preliminary exploration and limited materials research. The facilities will be operated by a crew of 4 for approximately 10 Earth days. The growth phase will have facilities for larger scale materials research, closed-loop research, and liquid oxygen utilization. This phase will be permanently manned with a crew of eight.

The habitat and laboratory facilities were assumed to be constructed entirely from space station modules, nodes, and airlocks. Modules were 4.5 m in diameter by 13.3 m long. Nodes were 4.5 m in diameter by 6.0 m long. Both were aluminum cylindrical structures. An airlock was an aluminum sphere 3.7 m in diameter. The initial phase consisted of a habitat module, three nodes, and three airlocks. The growth phase consisted of two habitat modules, a laboratory module, six nodes, four airlocks, and an observatory. The configurations for the two phases are shown in Fig. 1. A space station node was used to model the observatory. The base was assumed to be either under a supporting structure covered by 2 m of lunar regolith or directly buried under 2 m of lunar regolith. Approximately 2 m of lunar regolith was estimated as sufficient to protect the crew from cosmic radiation (*Duke et al.*, 1985).

The Solar System Exploration Division at JSC identified four possible sites for the first base. They were Lacus Veris (87.5°W, 13°S), the South Pole, the Apollo 17 landing site (30°E, 20°N), and the Mare Nubium (10°W, 10°S).

LUNAR ENVIRONMENT

The lunar environment changes dramatically from day to night and from location to location. The lunar day lasts approximately 28 Earth days with 14 days of sunlight and 14 days of darkness. The lunar surface temperature can range from 374 K during the lunar noon (Earth day 7) to 120 K during the lunar night. Figure 2 shows the temperature variations over the lunar day at different latitudes. These plots were generated using an empirically derived equation from *McKay* (1963). The equation was modified to include the effects of the varying solar flux at different latitudes resulting in the following

$$T_{moon}\,(K) = 373.9(\cos\phi)^{.25}(\sin\theta)^{.167}$$

In addition, features of the lunar environment could protect a lunar base from these severe temperature variations. For example, there may be permanently shadowed regions near the poles that have consistently low temperatures (*Stimpson and Lucas*, 1972). The lunar regolith could be used as thermal protection because it is an excellent insulator with an average thermal conductivity of approximately 0.004 W/m-K (*Dalton and Hohmann*, 1972). The regolith immediately below the lunar surface could provide a stable thermal gradient that is relatively insensitive to the day/night surface temperature variations. The utilization of these features could enhance a TCS design.

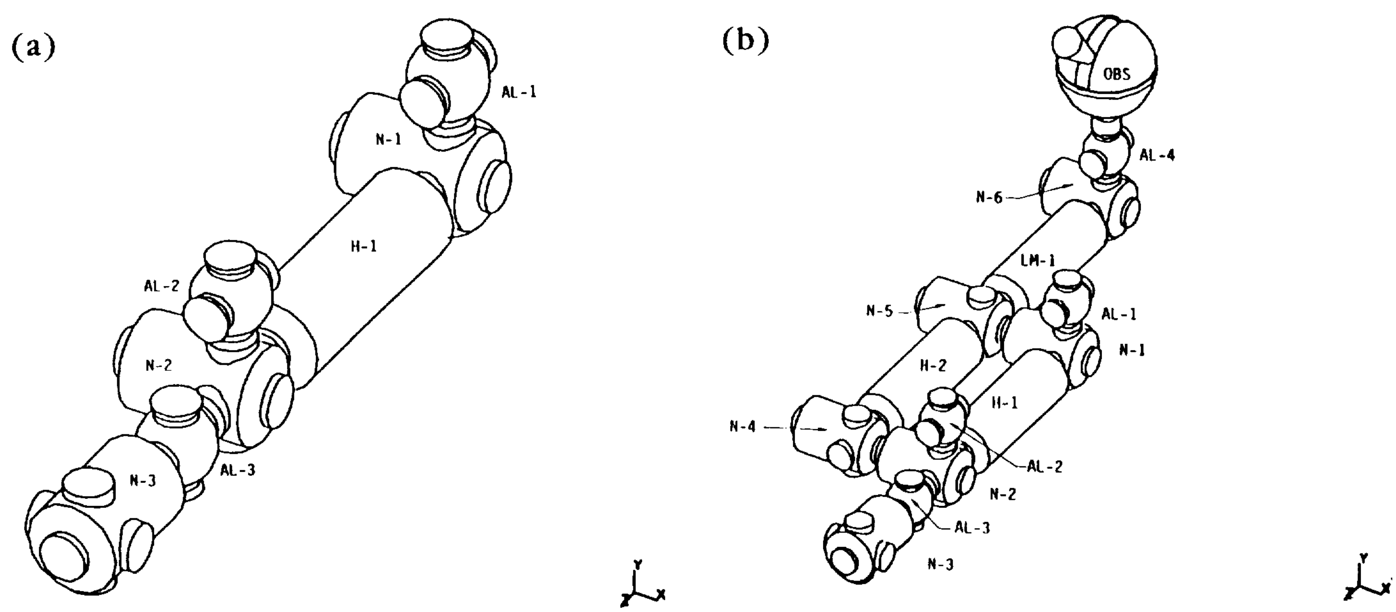


Fig. 1. Lunar base module configurations.

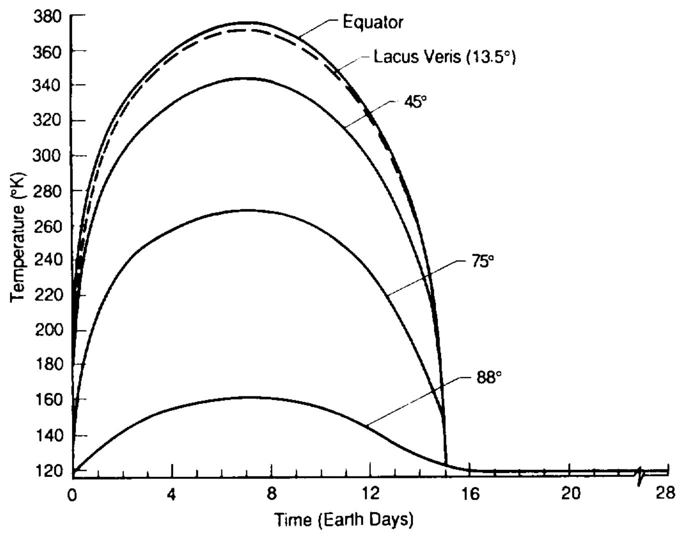


Fig. 2. Lunar surface temperature profile at different latitudes.

THERMAL CONTROL REQUIREMENTS

The TCS for the habitable areas of the base was designed to maintain the temperature inside the modules between 18°C and 24°C and to maintain the dew point temperature between 4°C and 16°C. To accomplish this, the equipment and metabolic heat loads must be actively removed, and the external gains and losses must be minimized.

The total heat loads assigned to each module, node, and airlock were selected based upon the specified load requirements of the space station (*NASA*, 1984). These loads are listed in Table 1 for heat acquired at 2°C and 21°C. Included in these loads are the metabolic sensible (crew) and latent (humidity) heat, as listed in Table 2.

The external heat gains and losses between the modules and the environment were calculated for three cases to determine if additional load requirements would be imposed upon the active thermal control system. The three cases considered were (1) a module protected under an aluminum supporting structure with 2 m of regolith on top, (2) a module directly buried under 2 m of regolith, and (3) a module directly on the lunar surface. The heat gains and losses of the modules protected with 2 m of regolith were negligible for modules both at the lower latitudinal sites (Lacus Versis, Apollo 17, and Mare Nubium) and at the South Pole. However, for a module directly on the surface (i.e., the observatory) at the lower latitudinal sites, there will be an added load of 2.2 kW heat gain during the hottest part of the lunar day, and there will be a heat loss of 1.7 kW during the night. For a module on the surface at the South Pole, there will be a heat loss over the entire day with a maximum heat loss at night of 1.7 kW. These added loads will be addressed in the design of the acquisition system. The details of the analysis are explained in the Appendix.

Using the heat loads listed in Table 1 for all the base modules, excluding node 3 (assumed to be a logistics module with no active TCS) and airlock 4 (used as access to the observatory with no active TCS), the maximum heat load for the initial phase is 65 kW at 21°C and 30 kW at 2°C. Likewise, the maximum heat load for the growth phase is 135 kW at 21°C and 66 kW at 2°C.

CONCEPTUAL DESIGN

The Lacus Veris, Apollo 17 landing, and the Mare Nubium sites experience essentially identical thermal environments because of their similar distances from the equator. Therefore, one TCS designed for the lower latitudinal regions could be used at all three sites. Since the lunar surface temperature variations become less pronounced at higher latitudes, the South Pole site will experience a different, more benign environment. Therefore, a separate TCS design may be needed.

Conceptual TCSs were designed to acquire the heat loads and reject them into the lunar environment for the South Pole and the lower latitudinal sites. The internal thermal requirements for the base at these locations were essentially identical. However, since the rejection environments are unique to location, the rejection systems for the South Pole and the lower latitudinal sites were evaluated separately.

Acquisition Considerations and System Design Estimates

The ambient environment in the lunar base modules and the heat loads acquired in the modules were similar to those projected for the space station modules; therefore, the space station's acquisition technology was used for the lunar base. However, the weight, volume, and power distributions were different because of the configuration of the base modules and the layout of the acquisition system.

Each module's acquisition system was sized to accommodate the heat loads specified in Table 1, although this capacity was not immediately required. Included in these loads was 2.36 kW for each air temperature and humidity control system designed to remove metabolic sensible and latent heat loads (Table 2) and to cool equipment in case of emergency.

The air temperature and humidity control heat loads were charged to node 1 for the initial phase and to nodes 5 and 6 for the growth phase. Two relative humidity and sensible heat exchangers will remain in operation in nodes 1 and 5, while the relative humidity and sensible heat exchangers in node 6 will be used to meet safe haven requirements. If the base were located at a lower latitudinal site, the unit in node 6 would also be used

TABLE 1. Selected heat loads in the habitable areas.

Module	Heat Load 2°C	(kW/module) 21°C
Habitation Module	10	15
Laboratory Module	10	15
Node	4	10
Airlock	4	10
Observatory	4	10

TABLE 2. Metabolic sensible and latent heat loads.

Type	Load	
Metabolic Sensible	0.086	kW/man
Latent		
Sweat and respiration water	1.82	kg/man day
Hygiene water	0.44	kg/man day
Food preparation water	0.03	kg/man day
Experiment water	0.45	kg/man day
Laundry water	0.06	kg/man day

to provide the observatory with the added cooling and heating requirements during the hottest and coldest times of the lunar day. If the base were located at the South Pole, the heat exchangers would need to provide additional heating during the entire lunar day/night to compensate for the heat losses to the environment.

The remaining module heat loads were accommodated by cold plates designed to meet all normal equipment cooling requirements and customer needs. The cold plates are arranged in parallel to provide isothermal operating conditions (Fig. 3). The cold plates are stainless steel and are cooled by either the 2°C or 21°C pumped water loop. The available cold plates in each module are listed in Table 3.

The module heat loads were pumped to the bus heat exchangers located near the main transport line. Some modules contain support loops to pump the heat acquired in one location through another module to the bus heat exchanger to reduce the lengths of external transport lines. A typical layout is shown in Figs. 4a and 4b for the initial and growth phases, respectively. Weight, volume, and power estimates for the acquisition systems in the initial and growth configurations are shown in Tables 4 and 5, respectively.

The weight, volume, and power estimates were computed using the Emulation-Simulation Thermal Control Model for Space Station Application developed by LaRC and Georgia Institute of Technology (*Hall et al.,* 1986; *Colwell and Hartley,* 1988) and data obtained from Marshall Space Flight Center (MSFC). Estimates for the air temperature and humidity control system contained relative humidity and sensible heat exchangers, a water separator, and redundant water transport lines operating at 2°C. It also included a ventilation system composed of ducting, intake filters, and fan packages. The above estimates for the equipment heat acquisition loops contained cold plates, redundant pump packages, redundant liquid water transport loops, disconnects, valves, flex hoses, controllers, transducers, sensors, etc. The above estimates for the support loops contained redundant transport lines, fittings, controllers, disconnects, transducers, and sensors.

Heat Rejection Considerations

The acquired heat loads on the space station are transported from the module bus heat exchangers via separate pumped two-phase ammonia loops at 2°C and 21°C to aluminum heat pipe

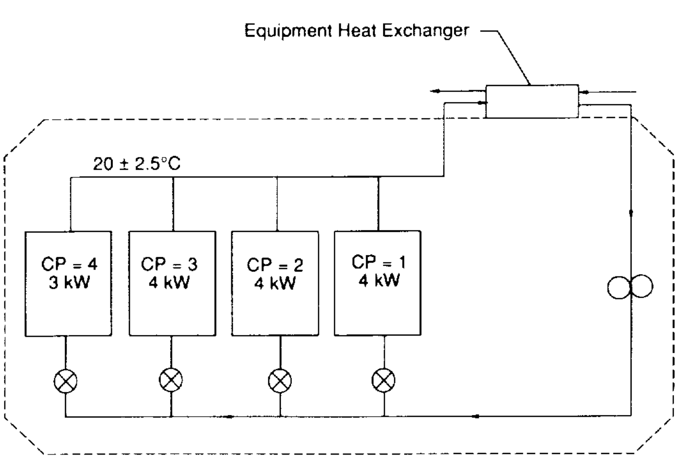


Fig. 3. Typical cold plate configuration for an integrated module.

TABLE 3. Equipment loads in each module.

Module	Temp of Loop (°C)	Number of Cold Plates	Load on Each (kW) 1	2	3	4
Habitation	2	3	2.0	4.0	4.0	0.0
	21	4	4.0	4.0	4.0	3.0
Laboratory	2	3	2.0	4.0	4.0	0.0
	21	4	4.0	4.0	4.0	3.0
Node (2,4)	2	2	2.0	2.0	0.0	0.0
	21	4	2.5	2.5	2.5	2.5
Node (1,5,6)	2	1	1.6	0.0	0.0	0.0
	21	4	2.5	2.5	2.5	2.5
Airlock (1,2,3)	2	2	2.0	2.0	0.0	0.0
	21	3	5.0	2.5	2.5	0.0
Observatory	2	2	2.0	2.0	0.0	0.0
	21	4	2.5	2.5	2.5	2.5

radiators. An 8° temperature drop was assumed between the acquisition cold plates and the heat pipe radiators, resulting in radiator rejection temperatures of -6°C and 13°C. In the space station environment, the radiators can be oriented to reject an average of 100 W/m^2 at -6°C and 160 W/m^2 at 13°C.

The thermal environment is more severe on the lunar surface, resulting from direct solar flux and infrared (IR) flux from the lunar surface. These factors degrade the average heat rejection capability of the radiators. In some instances these effects prevent the radiators from emitting heat and may cause them to gain heat from the external environment.

The rejection capability of the radiators was estimated using the following equation

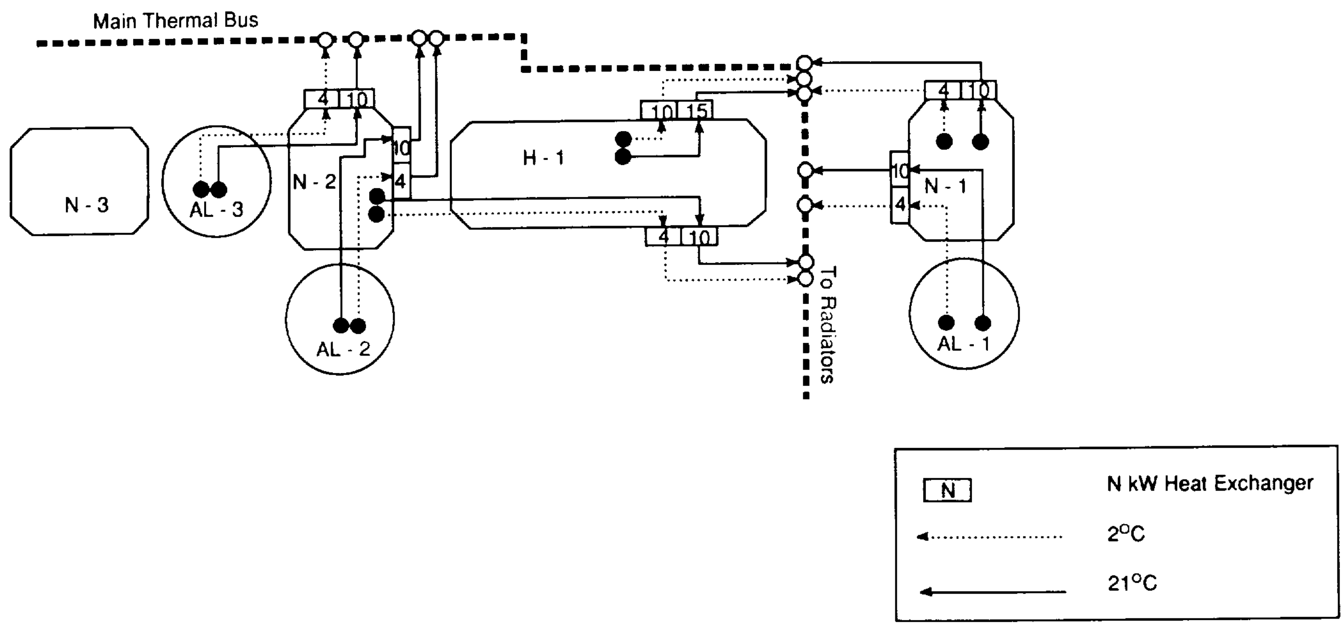
$$q = \epsilon\sigma(T^4_{rad} - T^4_{sink})$$

where q is the radiator heat rejection capability in W/m^2 and T_{sink} is the effective environmental temperature (K). The sink temperature represents the added effects of cold space, solar flux, and IR flux from the lunar surface. The sink temperature calculations were based on the methodology presented in *Dallas et al.* (1971). They will depend on the latitude and orientation of the radiators, the time of day, and the radiator's surface properties. The radiators in this analysis were assumed to have an end-of-life emissivity of 0.80 and an absorptivity of 0.30 (*NASA,* 1984).

Computer programs were generated to calculate the variations in the heat rejection capability of the radiators over the lunar day for various orientations at different latitudes. Three orientations were considered. They included (1) a vertical radiator perpendicular to the plane of the solar ecliptic, (2) a vertical radiator parallel to the plane of the ecliptic, and (3) a horizontal radiator insulated from the lunar surface (Fig. 5). The total heat rejection capability calculated in the program represented the amount of heat per square meter of radiator panel. That is, if a vertical two-sided radiator had a heat flux of 200 W/m^2, it would reject 100 W/m^2 per side. Likewise, if a horizontal radiator had a heat flux of 200 W/m^2, it would reject 200 W/m^2 from one side. If a positive heat flux were calculated, the radiator would radiate heat to the environment. If, however, a negative heat flux were calculated, the radiator would gain heat. These conventions are shown in Fig. 6.

Heat rejection at the South Pole. Figure 7 shows radiator heat rejection capability over the lunar day and night for radiator wall temperatures of -6°C and 13°C. Figure 7a indicates that horizontal radiators would provide the base with a capability that is continuously above the 100 W/m^2 average rejection capability of a space station radiator at -6°C. The other orientations fall

(a)



(b)

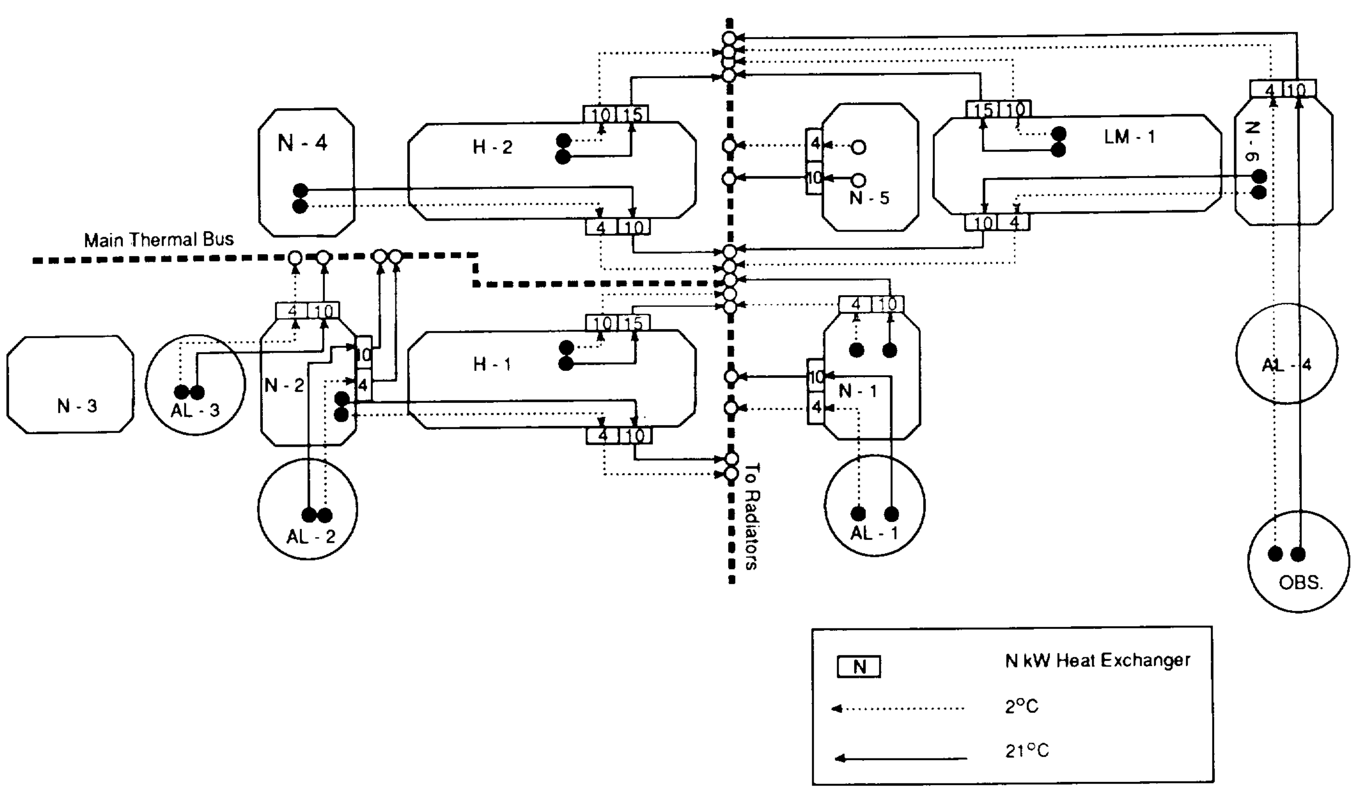


Fig. 4. **(a)** Initial phase layout of acquisition system. **(b)** Growth phase layout of acquisition system.

TABLE 4. Acquisition summary: Initial phase.

Item		Habitation Module-1	Node-1	Node-2	Air Lock-1	Air Lock-2	Air Lock-3
Weight (kg)							
Air Temperature and Humidity Control		149	143	57	57	57	57
Equipment Heat Acquisition	2°C	355	68	104	100	100	100
	21°C	390	200	191	195	195	195
Support Loop	(2°C and 21°C)	81	73	146	0	0	0
Total		975	484	498	352	352	352
Volume (m^3)							
Air Temperature and Humidity Control		1.73	0.71	0.40	0.40	0.40	0.40
Equipment Heat Acquisition	2°C	0.21	0.07	0.09	0.08	0.08	0.08
	21°C	0.22	0.10	0.10	0.10	0.10	0.10
Support Loop	(2°C and 21°C)	0.04	0.03	0.07	0	0	0
Total		2.20	0.91	0.66	0.58	0.58	0.58
Power (kW)							
Air Temperature and Humidity Control		0.49	1.04	0.15	0.15	0.15	0.15
Equipment Heat Acquisition	2°C	0.32	0.02	0.07	0.07	0.07	0.07
	21°C	0.29	0.18	0.18	0.19	0.19	0.19
Support Loop	(2°C and 21°C)	0.03	0.03	0.06	0	0	0
Total		1.13	1.27	0.46	0.41	0.41	0.41

TABLE 5. Acquisition summary: Growth phase.

Item		Habitation Module-2	Laboratory Module-1	Node-3	Node-4	Node-5	Node-6	Air Lock-4	Observ-atory
Weight (kg)									
Air Temperature and Humidity Control		149	149	57	57	143	143	57	57
Equipment Heat Acquisition	2°C	355	355	0	104	68	68	0	104
	21°C	390	390	0	191	191	191	0	191
Support Loop	(2°C and 21°C)	81	81	0	0	0	146	46	0
Total		975	975	57	352	402	548	103	352
Volume (m^3)									
Air Temperature and Humidity Control		1.73	1.73	0.40	0.40	0.71	0.71	0.40	0.40
Equipment Heat Acquisition	2°C	0.21	0.21	0	0.09	0.07	0.07	0	0.09
	21°C	0.22	0.22	0	0.10	0.10	0.10	0	0.10
Support Loop	(2°C and 21°C)	0.04	0.04	0	0	0	0.07	0.02	0
Total		2.20	2.20	0.40	0.59	0.88	0.95	0.42	0.59
Power (kW)									
Air Temperature and Humidity Control		0.48	0.48	0.15	0.15	1.04	1.04	0.15	0.15
Equipment Heat Acquisition	2°C	0.32	0.22	0	0.07	0.02	0.02	0	0.07
	21°C	0.29	0.29	0	0.18	0.18	0.18	0	0.18
Support Loop	(2°C and 21°C)	0.03	0.03	0	0	0	0.06	0.03	0
Total		1.13	1.13	0.15	0.40	1.24	1.30	0.18	0.40

below the 100 W/m^2 level during periods of large solar and IR fluxes. Figure 7b indicates that the radiator rejection capability for all orientations is above the 160 W/m^2 average rejection capability of a space station radiator at 13°C. The heat rejection for the horizontal radiator configuration also provides a comparatively constant flux.

The results of this analysis indicate that a space station-type radiator assembly with a horizontal radiator orientation could accommodate the thermal environment of the South Pole without any major modifications or enhancements to the system.

Heat rejection at lower latitudinal sites. The rejection capabilities for three radiator orientations with a -6°C wall temperature and a 13°C wall temperature at Lacus Veris are shown in Figs. 8a and 8b, respectively. As indicated by the figures, none of the orientations for either temperature loop provides a capability that meets the 100 W/m^2 level for the entire day. In fact, the heat fluxes become negative for large portions of the lunar day. The heat gain experienced by the radiators can lead to elevated radiator temperatures and thermal control disfunction.

Two possible enhancements to improve rejection capability were identified. The first was to lower the sink temperature by using reflective insulating blankets, which reduce the lunar IR flux on the radiators. The second was to elevate the rejection temperature above the sink temperature using a heat pump assembly. Thermal storage was considered; however, the large heat loads for long durations would result in a massive system using current storage technology (*NASA*, 1985). The use of lunar regolith for thermal storage may require extremely large heat transfer areas because of its low conductance.

The lunar heat flux affecting a vertical radiator's rejection capability is a function of the lunar surface temperature, the view factor of the radiator to the surface, and the radiator emissivity.

By covering the surface in the proximity of the radiator with highly reflective, low solar absorptivity blankets, the lunar surface temperature can be significantly reduced, which may reduce the sink temperature enough below the radiator wall temperature to produce reasonable rejection capability. This surface temperature reduction must be traded against an increase in solar flux, which results from solar radiation reflecting off the blankets onto the radiator surface.

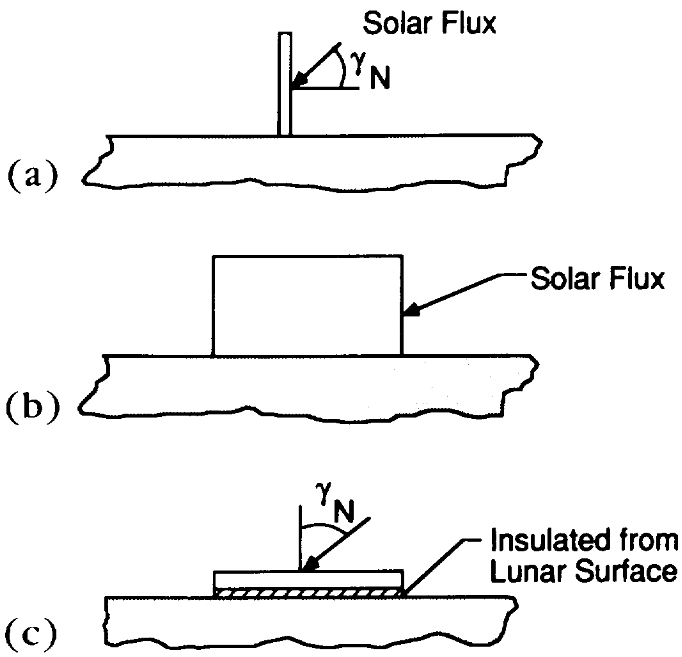


Fig. 5. Radiator orientations.

A computer model was generated to determine the minimum blanket size required to produce favorable sink temperatures. The computer model simulated a vertical, two-sided radiator oriented parallel to the solar ecliptic. Radiator and blanket surface temperatures could be calculated at any latitude on the Moon. The reflective insulating blankets were assumed to be adiabatic, with a very low thermal conductivity. Blanket size was measured on the basis of blanket width to radiator length (W/L), vs. radiator height to radiator length (H/L) as defined in Fig. 9.

From the above model, it was found that the reflective blankets significantly reduced the radiator sink temperature for radiator height to blanket width (H/W) ratios above 0.3 (H/L divided by W/L from Fig. 10). If the insulation area were increased further, only a slight reduction in T_{sink} would occur.

Based on a H/W ratio of 0.3, sink temperatures of radiators surrounded by reflective insulating blankets were calculated at Lacus Veris over the length of the lunar day. The blanket was assumed to have α/ϵ equal to 0.1/0.9. The calculated sink temperatures were compared with those for the uninsulated case, as shown in Fig. 11. From the figure, it is shown that at lunar noon, a 50°C temperature drop is achieved in the sink temperature. However, the sink temperature still remains higher than the low rejection temperature loop, primarily because of the increase in reflected solar flux. Consequently, a radiator heat gain is still present for parts of the lunar day. The insulating blankets do not provide sufficient improvement in the rejection capability.

An alternative to lowering the sink temperature is to raise the radiator temperature significantly above the existing sink temperature. This could be done by using a heat pump system. The system evaluated in this study was a cascaded vapor cycle system (VCS) coupled with standard space station ammonia heat pipe radiators.

A schematic of a two-loop cascaded VCS is shown in Fig. 12 (S. T. Worley, personal communication, 1988). The central bus working fluid enters the VCS in a superheated state and is then further pressurized by the compressor. The refrigerant is then cooled to a saturated liquid state in the evaporator/condensor and then subcooled before finally returning to the central bus. The

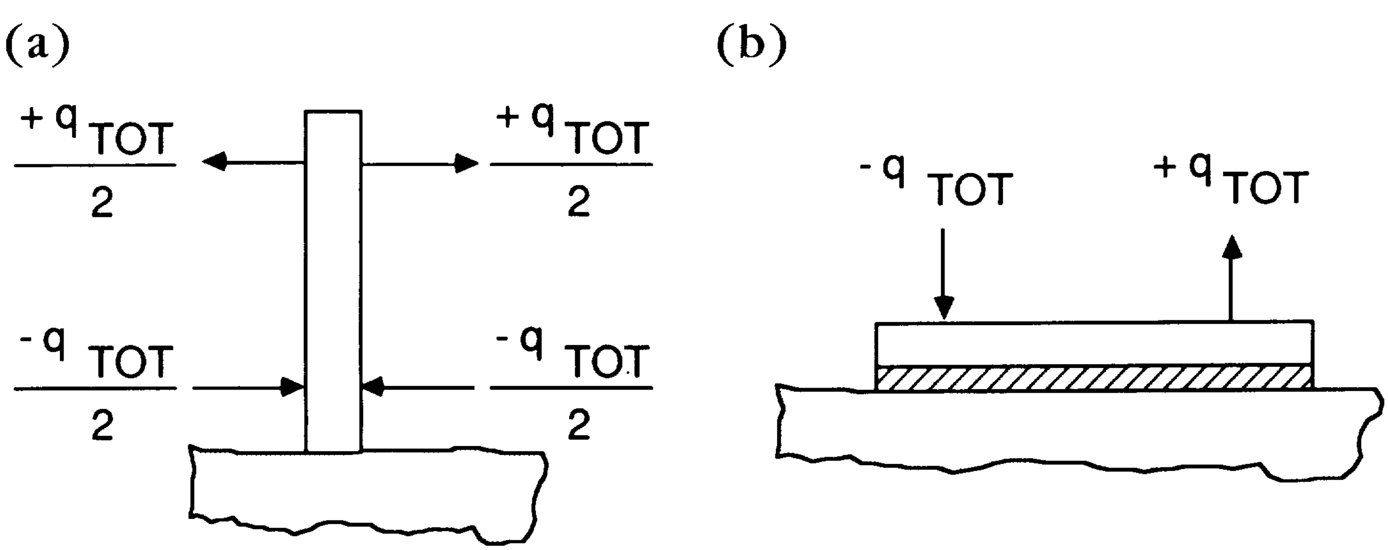


Fig. 6. Heat flux conventions used.

working fluid in the second loop picks up heat in the evaporator/condensor and proceeds through a similar process, where the heat is removed from the radiator at an elevated temperature.

A cascaded VCS was selected over a single-loop VCS to allow for more efficient compression and temperature ratios over the compressors. The refrigerants were selected based on the temperature excursions involved in each loop. The cascaded system would allow for stagewise operation, that is, each added stage could be run as an increased radiator temperature was needed to reject to the increasing sink temperature encountered over the lunar day. This would enable the radiator to operate with a more constant heat flux. The heat rejection capability variations from vertical radiators (parallel to the solar ecliptic) over the lunar day at Lacus Veris are illustrated in Fig. 13. During days 0-2 and days 12-14, the second stage of the cascaded system would be operating while the first-stage compressor was bypassed, during days 3-11 both compressor loops would be in operation, and during days 15-28 no compressors would be in operation.

The coinciding power requirements for the initial phase are shown in Fig. 14. The use of the VCS would increase power requirements by up to 50 kW. The first loop compressor required 20.5 kW and the second loop compressor required 29.5 kW. The use of the VCS would also increase the amount of heat to be rejected. The total heat load to be rejected equals the heat acquired in the habitable areas plus the heat imparted to the working fluid by the compressors. A stagewise operation would, however, minimize the extra power requirements and the extra amount of heat to be rejected during the portions of the lunar day when one or both loops were bypassed.

Table 6 lists the maximum and minimum radiator rejection capabilities (q), areas required for heat rejection, and the total heat loads to be rejected for the initial phase. By selecting a final rejection temperature of 360 K, a midstage loop temperature of 311 K can be obtained for an effective operating range of the system. These temperatures will require similar maximum radiator rejection areas (257, 242, 226 m^2) during minimum rejection

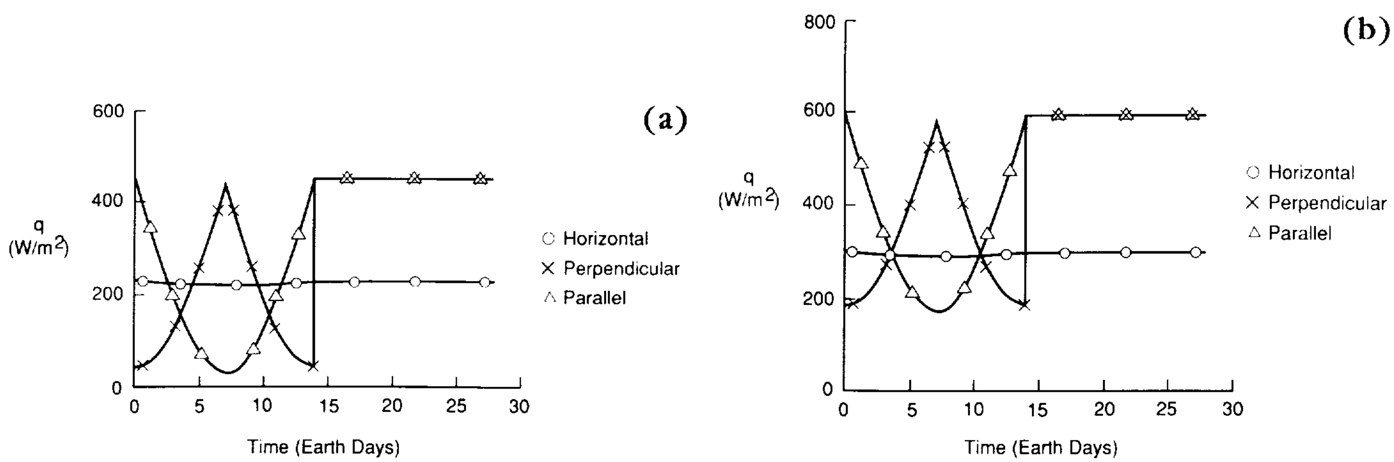


Fig. 7. **(a)** Heat rejection capability for radiators with a wall temperature of -6°C at the South Pole. **(b)** Heat rejection capability for radiators with a wall temperature of 13°C at the South Pole.

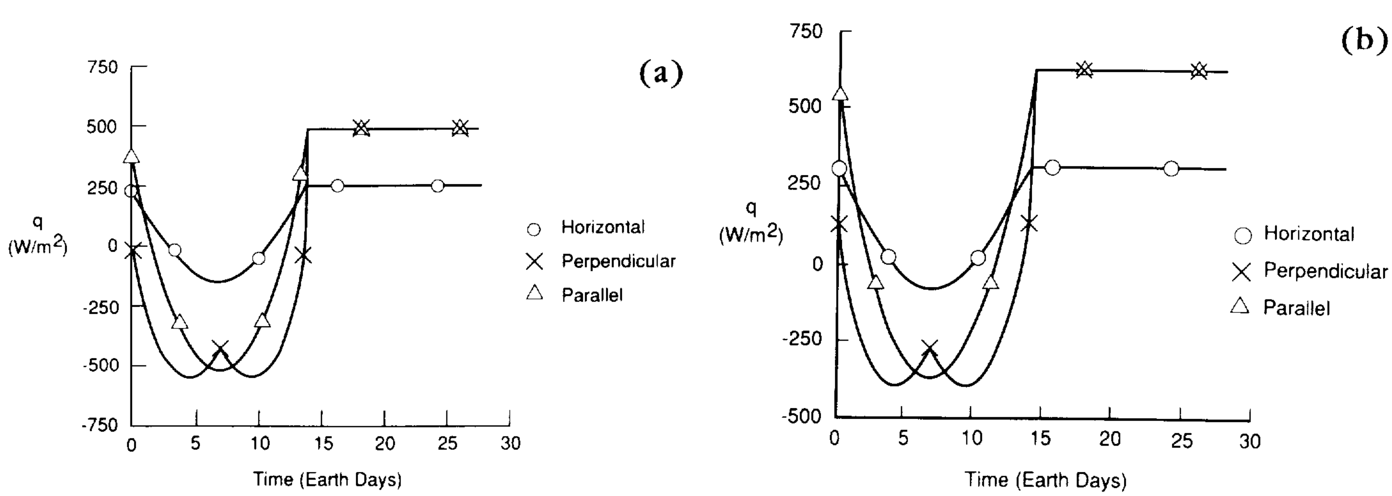


Fig. 8. **(a)** Heat rejection capability for radiators with a wall temperature of -6°C at Lacus Veris. **(b)** Heat rejection capability for radiators with a wall temperature of 13°C at Lacus Veris.

times. This temperature selection would therefore reduce the amount of total radiator area required.

As shown in Fig. 13, the stagewise operation of the VCS still results in fairly wide excursions in the heat rejection capability ($420 W/m^2$ to $900 W/m^2$). Since the area of the radiators is based on the minimum heat rejection capability, the potential exists for a radiator to over-reject during times when the radiator flux is larger than the design level. This can cause thermal and fluid imbalances in the radiator and the rest of the TCS.

A three- or four-stage refrigeration system may be considered as a means to provide a more constant heat flux for the radiators and to further reduce the overall power requirements. However, as the number of refrigeration stages increases, the maintenance and the complexity of the system are expected to increase, and the reliability is expected to decrease. Other means of minimizing the effects of the high peaks on Fig. 13 would be to use louvers or variable conductance heat pipes.

Louvers function by changing the effective α/ϵ ratio of the radiator (*Agrawal*, 1986). This could be accomplished by opening or closing the louver blades over the highly emisssive radiator surface, thereby increasing or decreasing the effective emittance of the radiator. This concept could be used to help reduce the peaks shown in Fig. 13 by closing the louvers (reducing the emittance) during the times when the flux capability is significantly

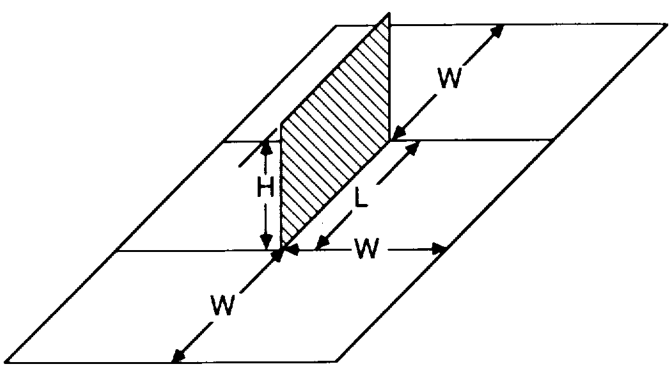


Fig. 9. Radiator and reflective insulation blanket model.

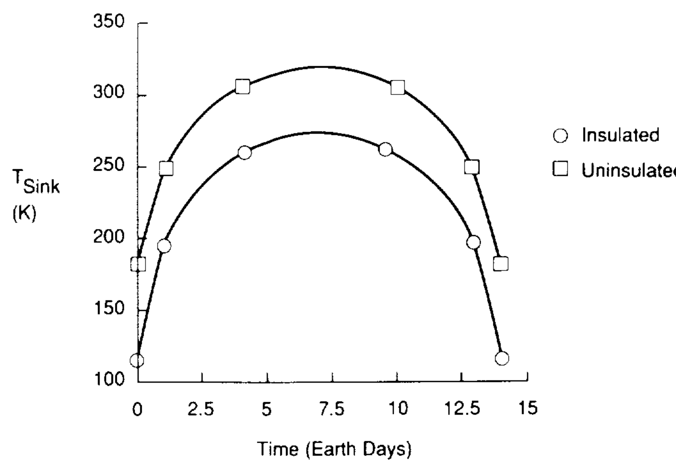


Fig. 11. Uninsulated vs. insulated sink temperatures over the lunar day for a radiator at Lacus Veris.

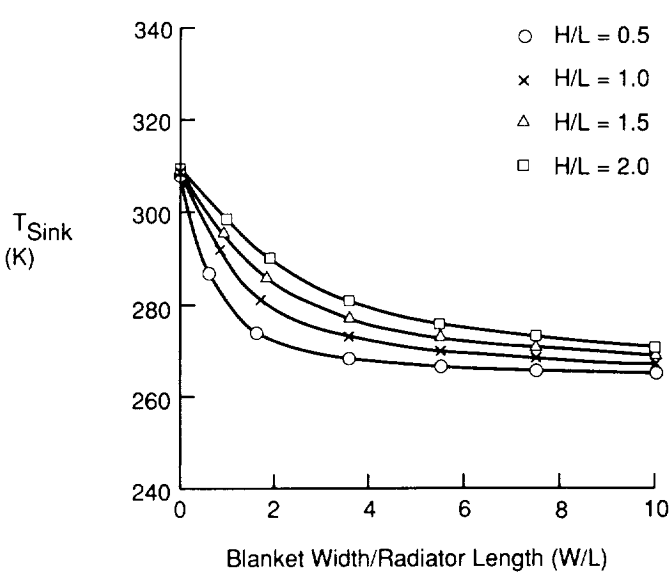


Fig. 10. Effective sink temperatures at noon for a radiator with varying amounts of reflective insulation blankets at Lacus Veris.

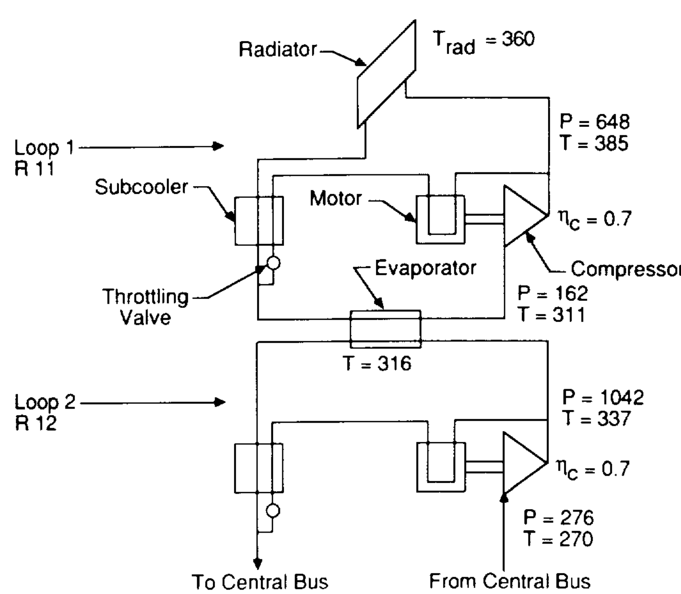


Fig. 12. Two-loop cascaded vapor cycle system.

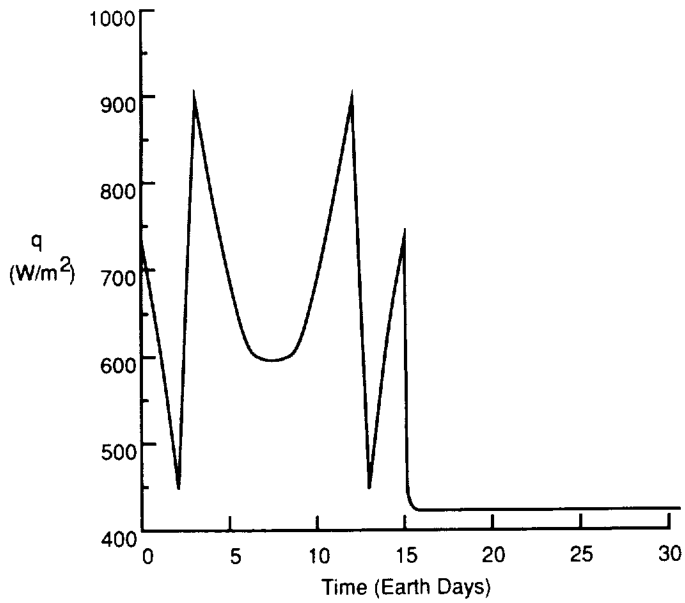


Fig. 13. Rejection capability of the radiator over the lunar day for a two-loop cascaded vapor cycle system in stagewise operation.

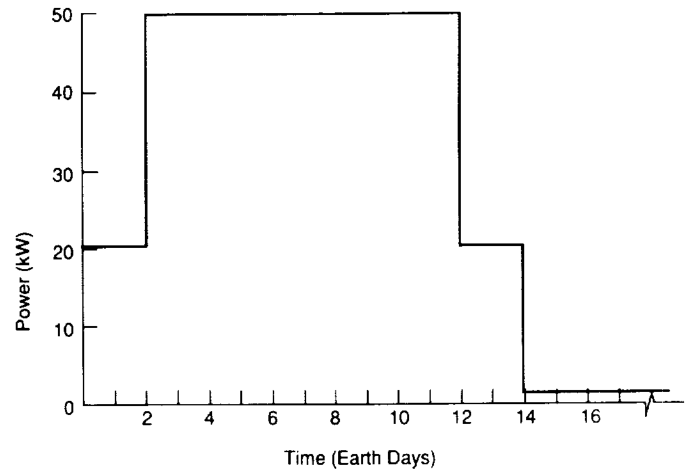


Fig. 14. Initial phase power summary for transportation and rejection systems.

TABLE 6. Radiator area requirements for the initial phase.

Time (Earth Days)	T_{rad}(K)	Total Q (kW)	Minimum q (W/m^2)	Maximum Area (m^2)	Maximum q (W/m^2)	Minimum Area (m^2)
0-2	311	115.5	450	257	750	154
3-11	360	145.0	600	242	900	161
12-14	311	115.5	450	257	750	154
15-28	262	95.0	420	226	420	226

over design level and by opening the louvers during design level operation. The standard spacecraft louvers are usually actuated by temperature-sensitive bimetallic springs that contract or expand in response to temperature differences from a single baseline temperature. For lunar base application, this actuation technique would not be acceptable because of the multiple temperature ranges in which the radiators must operate. Consequently, some type of electrically controlled actuator could be used.

An alternative concept, the variable conductance heat pipe radiator, could help control the rejection capability by controlling the actual amount of radiator surface area being used to reject heat. The concept consists of a heat pipe radiator filled with an appropriate working fluid connected to a large reservoir of inert gas that is pressurized to the saturation vapor pressure of the working fluid at the appropriate operating temperature (*Dunn and Reay,* 1978). If the heat input should rise from the design level, a resulting slight rise in temperature would increase the pressure of the working fluid. The working fluid would push inert gas back into the reservoir, thus exposing more radiator area for heat rejection, which would allow the temperataure to restabilize. If the heat input were reduced, the opposite effect would occur, that is, the radiator rejection area would decrease. An increase in rejection capability as a result of reduced external sink temperature or increased radiator temperature would also produce a reduction in active radiator rejection area. This reduction would then prevent imbalances by reducing the heat actually rejected to the appropriate levels. Since the rejection system was designed to function at three different operating temperatures (resulting from stagewise operation), the inert gas pressure must be adjusted to match the changing saturation vapor pressure of the working fluid at these different temperatures. This could be done by heating the inert gas using electrical or other types of heaters.

Heat Rejection System Design Estimates

The weight, volume, and power were calculated for the transport and rejection systems at the South Pole and Lacus Veris. In both cases, the transport system results included the bus heat exchangers, working fluid, and the lines shown in Fig. 6 plus an extra 10.0 m of lines out to the radiators. The transport lines were aluminum and were sized to accommodate the growth phase heat load (201 kW) when initially installed. The system also included a redundant set of lines for each temperature loop, pump packages, disconnects, valves, and sensors. In both cases, the rejection system was designed to evolve along with the increasing heat loads of the base. The rejection summary results included the radiator panels, clamp mechanisms, and the bus/radiator heat exchangers.

System design estimates at the South Pole. The space station heat rejection and transport technologies could be easily adapted for a lunar base located on the South Pole. The transportation system would be separate, pumped, two-phase ammonia loops operating at 2°C and 21°C. The rejection system estimates included a horizontal ammonia heat pipe radiator that provides a nearly constant heat flux during the lunar day and night (Figs. 7a,b). No rejection enhancement techniques were required. The system summaries are shown in Table 7. The Emulation-Simulation Thermal Control Model program was used to size the transport lines (*Hall et al.,* 1986; *Colwell and Hartley,* 1986). The weight and volume of the extra equipment in the transport system, such as the bus heat exchangers, insulation, valves, and pump packages, were determined using JSC's internal thermal control database for Phase B of the space station. The heat rejection system was also sized using data from JSC. This configuration could be used for base locations more than 70° from the equator; however, the system estimates would increase as the site moves farther from the pole.

System design estimates at the lower latitudinal regions. A two-loop cascaded VCS was selected for use at Lacus Veris with the space station ammonia heat pipe radiators as shown in Fig. 14. Each VCS was sized to accommodate 100 kW. The initial phase included one vapor cycle system and the growth phase included two vapor cycle systems. The VCS estimates included the compressor, evaporator, and the subcooler, plus the interstage line and the Freon 11 working fluid. The heat was transported from the modules to the rejection system by a single-temperature two-phase Freon 12 loop operating at -3°C. A vertical radiator oriented parallel to the solar ecliptic was selected because of the larger heat rejection capability obtainable for each stage temperature. Variable conductance heat pipes may be required to provide a more constant flux from the radiators; however, they were not included in these estimates. Evaporator and compressor bypass loops will be used for stagewise operation. The system summaries are shown in Table 8. The heat pump system estimates were obtained from the Sunstrand Corporation. The other system components were sized as discussed in the previous section. This system would also be adequate for other lower latitude base locations, with the estimates decreasing as the latitudes increase.

TABLE 7. Transport and rejection summary for initial and growth phases at the South Pole.

Phase		Weight (kg)	Volume (m^3)	Power (kW)
Initial				
Transport	2°C	696	8	0.33
	21°C	825	9	0.33
Rejection	2°C	1,319	4	0
	21°C	2,167	6	0
Total		5,007	27	0.66
Growth				
Transport	2/oC	1,518	17	0.66
	21°C	1,755	19	0.66
Rejection	2°C	2,920	8	0
	21°C	4,488	13	0
Total		10,681	57	1.32

TABLE 8. Transport and rejection summaries for the initial and growth phases at lower latitudinal regions.

Phase	Weight (kg)	Volume (m^3)	Power (kW)
Initial			
Heat pump	75	1	50.0
Transport	902	7	0.33
Rejection	3338	10	0
Total	4315	18	50.33
Growth			
Heat pump	150	2	100.0
Transport	2044	15	0.66
Rejection	6979	21	0
Total	9173	38	100.66

CONCLUDING REMARKS

A lunar base thermal control conceptual design derived from space station technology has been presented. The impact of landing site selection for both a South Pole site and low latitude sites was discussed. Alternate technologies were identified for those areas where space station technologies were not compatible with the lunar environment. Lunar resources that showed potential to enhance the thermal control concept were evaluated.

The lunar regolith was used as an insulator to minimize heat transfer from the base modules to the lunar environment. Space station acquisition technology was adequate for a base located at the South Pole or near the equator, whereas space station transport and rejection technology could only be adapted for a base at the South Pole. Lower latitudinal base sites will require alternate heat rejection techniques to accommodate the high environment sink temperatures encountered near the equator. A vapor cycle system was selected to provide this function. Conceptual designs were formulated and include weight, power, and volume estimates.

APPENDIX: PASSIVE THERMAL CONTROL ANALYSIS

The module's passive thermal control capability was evaluated to determine if the space station's multilayer insulation (MLI) will adequately protect the habitable areas from the lunar environment. The space station modules were assumed to be protected with MLI having an α/ϵ ratio of 0.8/0.8 (*NASA,* 1984) and an average thermal conductance between 0.16 W/m^2-K at 310 K and 0.05 W/m^2-K at 225 K (from Apollo correlation). Three cases were considered to determine if the space station's insulation would prevent large heat gains into the module during the lunar day and prevent large heat losses from the modules during the lunar night.

Case One

For case one, the module was assumed to be protected under an aluminum supporting structure with 2 m of regolith on top. The system was modeled as concentric cylinders to simplify calculations (Fig. A-1). Calculations using this geometry will provide conservative results. In this case the entire surface area of the "soil shell" around the module will experience the extreme day/night temperature variations, whereas, when actually deployed on the Moon, only half of the module's "soil shell" will experience the temperature extremes. The other half will experience the more benign temperature environment several meters below the lunar

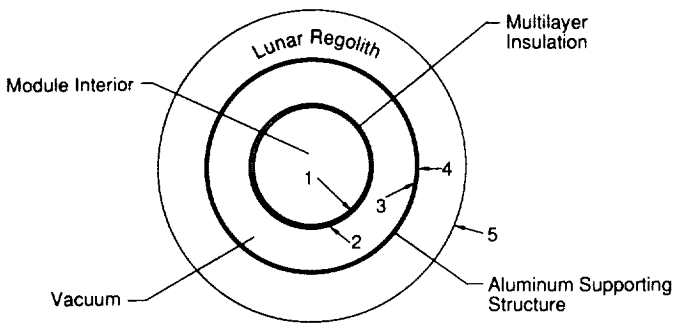


Fig. A-1. Concentric approximation for a lunar module under an aluminum structure and lunar regolith.

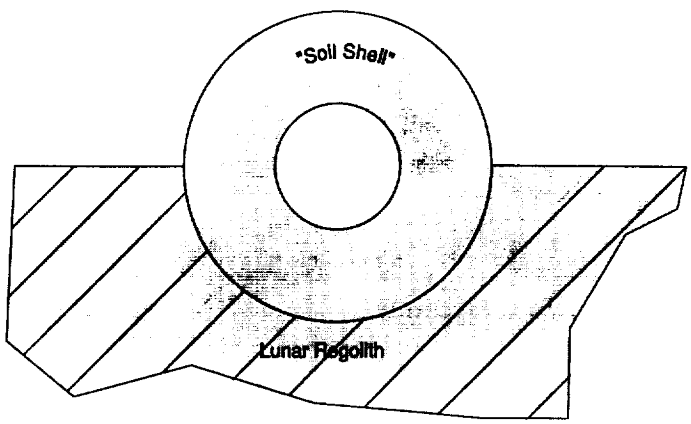


Fig. A-2. Actual environment of module's "soil shell."

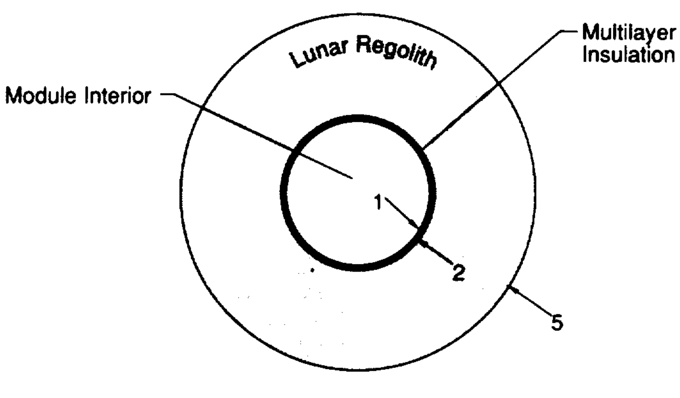


Fig. A-3. Concentric approximation for a lunar module buried directly under the lunar surface.

surface (Fig. A-2). The following equations were derived to determine the maximum heat exchange between the module and the environment at steady state

$$Q = 2\pi r_1 Hh(T_1 - T_2) = \frac{2\pi r_1 H\sigma(T_2^4 - T_3^4)}{\frac{1}{\epsilon_2} + \frac{r_1}{r_3}\left(\frac{1}{\epsilon_3} - 1\right)} =$$

$$\frac{2\pi Hk_{Al}(T_3 - T_4)}{ln\frac{r_4}{r_3}} = \frac{2\pi Hk_{reg}(T_4 - T_5)}{ln\frac{r_5}{r_4}}$$

where T_1 equals 294 K and T_5 equals either 374 K near the equator or 120 K during the lunar night. Solving for T_2, T_3, and T_4 yields a heat gain of 0.08 kW at lunar noon and a heat loss of 0.17 kW at night. These amounts of heat gain and heat loss are negligible compared to the estimated heat loads already in a habitation or laboratory module (0.3% and 0.7% of the 25-kW load, respectively). Thus, in this system the space station's MLI coupled with lunar regolith will provide adequate protection.

Case Two

In this case, the module was assumed to be buried 2 m directly below the lunar surface. Again, the system can be modeled as concentric cylinders (Fig. A-3). The following equation was derived to determine the maximum heat exchange between the module and the environment at steady state

$$Q = 2\pi r_1 Hh(T_1 - T_2) = \frac{2\pi Hk_{reg}(T_2 - T_5)}{ln\frac{r_5}{r_1}}$$

where T_1 equals 294 K and T_5 equals either 374 K at noon near the equator or 120 K during the lunar night. The compressive force of the regolith on the MLI may significantly increase its thermal conductance and, therefore, decrease its insulating capability. Thus, it was assumed that T_2 approaches T_1, resulting in a maximum heat gain at noon of 0.05 kW and a maximum heat loss at night of 0.11 kW. Again, the heat gain and loss are negligible compared to the heat loads already acquired in a habitation or laboratory module (0.2% and 0.4%, respectively); therefore, the space station's MLI coupled with lunar regolith will provide adequate protection.

Case Three

A third case must be considered, where a module is directly on the surface and not covered by any lunar regolith. An example of this situation was the observatory that would be on the surface. The following equation was derived to determine the maximum exchange between the module and the environment at steady state

$$Q = 2\pi r_1 Hh(T_1 - T_2) = 2\pi r_1 H\sigma\epsilon_2(T_2^4 - T_{sink}^4)$$

where T_1 equals 294 K and T_{sink} equals either 358 K at noon near the equator or 98 K during the lunar night. Solving for T_2 gives a maximum heat gain of 2.2 kW and a maximum heat loss of 1.7 kW in the lower latitudinal region. These loads are 7% and 9%, respectively, of the module's total heat load; therefore, extra air temperature control will be needed during the hottest parts

of the lunar day and during the night to provide the crew with a comfortable environment. At the South Pole T_1 equals 294 K and T_{sink} equals 285 K during maximum solar flux or 98 K during the lunar night. The module will lose heat over the entire lunar day/night, with a maximum heat loss of 1.7 kW during the lunar night. The maximum heat loss is 7% of a module's total heat load; therefore, extra air temperature control will be needed.

Acknowledgments. The authors wish to express appreciation to the Sundstrand Corporation for their help in the development of the lunar heat pump system.

REFERENCES

Agrawal B. N. (1986) *Design of Geosynchronous Spacecraft.* Prentice-Hall, Englewood Cliffs. 459 pp.

Colwell G. T. and Hartley J. G. (1988) *Development of an Emulation-Simulation Thermal Control Model for the Space Station Application.* NAG-1-551. 88 pp.

Dallas T., Diaguila A. J., and Saltsman J. F. (1971) *Design Studies on the Effects of Orientation, Lunation, and Location on the Performance of Lunar Radiators.* NASA TM-X-1846. 40 pp.

Dalton C. and Hohmann E., eds. (1972) *Conceptual Design of a Lunar Colony.* Univ. of Houston, Houston. 529 pp.

Duke M. B., Mendell W. W., Roberts B. B. (1985) Strategies for a permanent lunar base. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 57-68. Lunar and Planetary Institute, Houston.

Dunn P. D. and Reay D. A. (1978) *Heat Pipes*, 2nd edition. Pergamon, Oxford. 334 pp.

Hall J. B., Colwell G. T., and Hartley J. G. (1986) Evaluation of space station thermal control techniques. *Proc. Intersoc. Conf. Environ. Sys. 16th,* SAE Paper 860998. 16 pp.

MacKay D. B. (1963) *Design of Space Power Plants.* Prentice Hall, Toronto. 322 pp.

NASA (1984) *Space Station Reference Configuration Description.* JSC Publ. No. 19989, NASA Johnson Space Center, Houston. 786 pp.

NASA (1985) *Space Systems Technology Model*, 6th edition. NASA, Washington, DC.

Ride S. K. (1987) *Leadership and America's Future in Space: A Report to the Administrator.* U.S. Govt. Printing Office, Washington, DC. 63 pp.

Stimpson L. and Lucas J. W. (1972) Lunar thermal aspects from Surveyor data. In *Thermal Characteristics of the Moon, Vol. 28* (J. W. Lucas, ed.), pp. 121-150. MIT, Boston.

N93-14004

ADVANCED PHOTOVOLTAIC POWER SYSTEM TECHNOLOGY FOR LUNAR BASE APPLICATIONS

David J. Brinker and Dennis J. Flood

NASA Lewis Research Center
Cleveland OH 44135

INTRODUCTION

The establishment of a permanently manned presence on the lunar surface represents a formidable challenge to a broad spectrum of space technologies. While all the technologies that will be required to sustain the evolution of a lunar base from its initial establishment as an outpost to its final manifestation as a permanent, life-sustaining, and productive habitat are essential, the pacing technology for it all is the production of power. A new aspect of such an endeavor is that the "mission" requirements are no longer fixed, but will evolve over time. It is now necessary to examine and develop a time-dependent set of requirements for the power system, and to put into place an adequately supported research and development program that is properly phased to produce the needed technology at the right time. The Lewis Research Center, as the lead center for space power for the Office of Aeronautics and Space Technology (OAST), has taken the first steps in that direction with the implementation of a program in High Capacity Power and the impending implementation of programs in Surface Power and Rover Power. All the preceding initiatives are the outgrowth of planning activities that have been conducted by OAST over the past few years, and which have culminated in the establishment of the Civil Space Technology Initiative (CSTI) and the Pathfinder program. The High-Capacity Power program is an element of CSTI, and the Surface Power and Rover Power programs are elements of Pathfinder.

POWER SYSTEMS MASS COMPARISON

While the definition of a complete set of time-dependent requirements is an unfinished task, an understanding of key issues has been developed to help guide the focused technology programs mentioned above. Technologies intended for application on the lunar surface will be driven by mass considerations, primarily because of the high cost of payload delivery to the Moon. Even if the assumption is made that low operational cost cargo vessels will be available for transit from low Earth orbit (LEO) to the Moon, there will still be a high cost for delivery to LEO that must be considered. For comparison purposes the cost can be represented by a payload mass multiplication factor that takes into account the total launch mass required to deliver the intended lunar bases elements to LEO. Although a universally agreed-on value for such a multiplier does not exist, primarily because the exact nature of future heavy-lift launch capabilities is not known, a value of 5 has been assumed for this discussion, along with an assumed heavy-lift vehicle (HLV) payload capability of 92,000 kg (200,000 lb) to LEO. Such assumptions are not unreasonable with respect to future launch systems. No further justification for using them will be provided except to point out that doing so allows a quantitative comparison of power system alternatives in terms of "operational" impact—the number of launch vehicles required to deliver the system elements to LEO for subsequent transport to the lunar surface.

The key figure of merit for a photovoltaic array is the power per unit mass in watts per kilogram (W/kg). For a storage system the appropriate figure of merit is the amount of available energy per unit mass in watt-hours per kilogram (Whr/kg). The advanced power system uses an ultralightweight photovoltaic array and an advanced hydrogen-oxygen regenerative fuel cell (RFC) for storage. The figures of merit for both systems are listed in Table 1. Table 2 compares the system masses for a state-of-the-art photovoltaic generation/battery storage system sized to deliver 100 kW to a lunar base to that performance projected for an advanced version of such a system. Two cases are considered for the 336-hr lunar night: a 100% duty cycle and a 20% duty cycle. Also shown is the mass saved in delivering the advanced system to LEO, along with the resulting number of HLV launches saved, under the assumptions given above. The final column of the table shows the additional number of HLV launches that would be saved by using the SP-100 nuclear power system currently under development, and intended to have a specific power of 33 W/kg. The table provides compelling evidence that there is a substantial payoff to be had in developing the advanced PV/RFC technology, particularly when placed in the "operational" context of the weight saved at LEO. A third case also exists, that in which the astronauts' stay would be limited to the 336-hr lunar day with a night duty cycle of zero, or close enough to zero so that lander energy storage would be sufficient. In this scenario, only a photovoltaic array would have to be delivered to the lunar suface. A state-of-the-art PV array to supply 100 kWe has a mass of 1515 kg, while an advanced array would weigh only 333 kg, a significant savings under a restricted mass budget.

TABLE 1. Figure of merit comparisons for photovoltaic/electrochemical technology options.

	State-of-the-art	Advanced
Array	66 W/kg, OAST-1	300 W/kg, ultralightweight
Storage	14 Whr/kg, NiH battery	1000 Whr/kg, H-O RFC

TABLE 2. Comparison of current and advanced photovoltaic power systems for a manned lunar base.

Power Level (KWe)	Night Duty Cycle	SOA PV/battery Mass (kg)	ADV PV/RFC Mass (kg)	Weight Saved At LEO (kg)	HLV Launches Saved	Additional HLVS Saved with SP-100
100	100%	1,680,000	34,350	7,910,000	87	1.6
100	20%	336,420	7,133	1,580,000	17.4	0.2

Figure 1 provides a more graphic comparison between the mass of the SOA phovoltaic/battery system, the advanced PV/RFC system, and the SP-100 nuclear power system. As can be clearly seen, the advanced PV/RFC technology has the potential to reduce the mass of a 100-kWe lunar surface power system using state-of-the-art technology by more than a factor of 45, to a value less than 2.5% of the mass of the latter. (The SP-100 system, even though projected to be lighter than the advanced PV/RFC system by a factor of 10, will only save a little more than another 2% of the SOA system mass.) The long lunar night is clearly the major issue in determining the mass of the lunar base photovoltaic-electrochemical storage system. The key feature that allows such a large mass reduction is that the stored energy in an advanced RFC system is in the form of gaseous reactants stored in high-pressure tanks, with the result that the RFC can approach 1000 Whr/kg, a factor of 4 or 5 better than that projected for advanced batteries, and a factor of more than 60 better than SOA batteries (NiH, for example). The remainder of this paper contains a more detailed description of the technology that will be pursued in the Surface Power program to achieve these gains.

PHOTOVOLTAIC ARRAY TECHNOLOGY

The key figure of merit for a photovoltaic array is the power per unit mass, also referred to as the specific power. A photovoltaic array consists of a number of solar cells interconnected to provide the required voltage and current levels to the electrical load, usually through a power management and distribution system. The cells are mounted on a substrate that can be either rigid, such as honeycomb panels, or flexible, such as kapton. The cells, substrate, protective diodes, and wiring harness

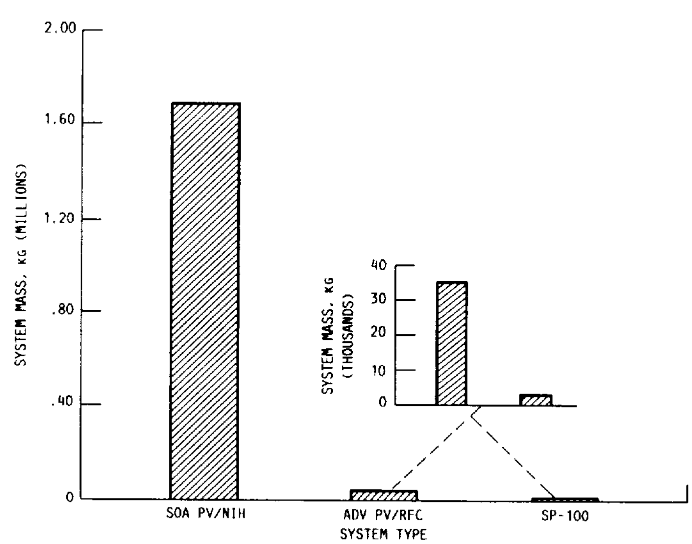


Fig. 1. Power systems mass comparison.

constitute the blanket. The remaining portion of the photovoltaic array is the mechanical structure, which includes the stowage container, the deployment mechanism, and the struts to maintain the blanket in a planar configuration pointed at the sun. Improvement in the specific power can be achieved through two different, although often coupled, approaches: increasing the conversion efficiency of the solar cell and reduction of the cell/blanket mass and/or array structure mass. Improvements in cell efficiency not only increase the array specific power, but also decrease array area if a fixed power level is required. For a system such as that envisioned for a rover vehicle, reduction in array area can be critical.

The program objective in the Surface Power program of Pathfinder is an array specific power of 300 W/kg at air mass zero (AM0) insolation (solar insolation at 1 AU). At present, lightweight photovoltaic arrays have been demonstrated on a space shuttle experiment (OAST-1) at 66 W/kg. A recent design, under development at the Jet Propulsion Laboratory for OAST, was established at 130 W/kg (*Scott-Monck and Stella,* 1986). This design, the Advanced Photovoltaic Solar Array (APSA), is based on 2-mil thick silicon cells. These two array designs are intended for the zero gravity conditions of LEO and geosynchronous Earth orbit (GEO). For lunar base applications, the array structure must be rugged enough to withstand the 1/6 *g* of the lunar surface.

To achieve the 300 W/kg specific power goal, two solar cell technologies have been identified for further development. These candidate cell types are ultrathin gallium arsenide (GaAs) and amorphous silicon (a-Si). Table 3 summarizes the current performance of technologies to be developed for a lunar base power system and their current performance. Gallium-arsenide cells are currently manufactured for space use at an efficiency of about 18%, with research devices achieving 21%. However, the current cell is too thick at 200-250 μm to give the performance needed for lunar base application. Fortunately, because it is a direct-gap semiconductor, GaAs absorbs all photons available for energy conversion within 3-4 μm of the impinging surface. This allows, unlike crystalline silicon, for an ultrathin, high-efficiency cell to be produced. Gallium-arsenide cells 5.5 μm thick have been fabricated using the cleaved lateral epitaxy for film transfer (CLEFT) process (*Fan et al.,* 1984), a technique in which a single-crystal thin GaAs layer is grown on a masked GaAs substrate and mechanically removed. Other processes, such as chemical thinning of the substrate, have also been successfully demonstrated as capable of producing high-quality, ultrathin layers and cells. Basic research and development in cell interconnectors and cell incorporation into a space-compatible blanket will be critical because of the brittleness of the ultrathin GaAs cells.

Amorphous silicon is primarily a terrestrial photovoltaic material; however, 9% space performance has been measured. The electronic structure of the disordered, amorphous material allows for total cell thickness of less than 1 μm and the use of flexible substrates. This is compatible with a very high blanket specific power and low-volume storage requirements. An extensive

TABLE 3. Technology status and design projections.

	Lunar Base Design	Current Performance
Photovoltaic Devices		
Gallium Arsenide	25% AMO Eff.	21%
Amorphous Silicon	15% AMO Eff.	9%
Array Structure		
Specific Power	300 W/kg (APSA)	66 W/kg (OAST-1)
Energy Storage		
High-Pressure Gas	1000 Whr/kg	300 Whr/kg (Primary
Regenerative Fuel Cell	60% Eff.	60%Eff. Fuel Cell)

manufacturing base already exists for a-Si terrestrial solar cells; however, several major hurdles must be overcome before it can be considered as a viable space cell candidate. Among these are low conversion efficiency and cell performance degradation under constant illumination. Although terrestrial arrays are manufactured on flexible, rugged substrates, few of the materials used are compatible with space requirements, necessitating basic studies in blanket materials and design.

Additional improvement in the photovoltaic array specific power can be achieved by minimizing the mass of the array structure. For the APSA design, the structure, blanket box, and deployment mechanism constitute more than 50% of the mass of the entire array. Research and development on the array structure are also warranted by the need, for the first time, for a space solar array to operate in a continuous gravity field. An APSA wing is pictured in Fig. 2, along with a detailed cross section of its blanket. Its design specific power of 130 W/kg is met with 13.5% efficient, 63-μm-thick silicon cells. Replacing the silicon cells with GaAs cells of 25% efficiency, assuming the same blanket mass and eliminating the 5% mass contingency built into the design, yields a specific power of 260 W/kg, quickly approaching the lunar base goal. This also assumes that a reduced gravity structure will weigh no more than the zero-*g* APSA structure, which is possible since manual deployment or erection is an option for a manned lunar base and could eliminate the deployment motor and mast. Figure 3 shows the approach taken by NASA toward a 300-W/kg zero-*g* array. Improvements in the structure and cell interconnector wiring, coupled with a high-efficiency cell, will enable attainment of this performance level. These improvements, as well as the overall design experience gained with zero-*g* arrays, will be incorporated into the lunar base array structure.

REGENERATIVE FUEL CELL TECHNOLOGY

At present only primary fuel cells exist, and regenerative cells, which do not limit mission time or power availability by the amount of hydrogen and oxygen that can be carried along, have not been designed. The primary focus of RFC research for a lunar base power system will be on fuel cell stack configurations including oxygen electrode catalysts, thermal and gas management, and lightweight, high-pressure, robust tank technologies. The principal effect of the 336-hr duration of the lunar night is the requirement for a very large fuel cell reactant mass. Therefore, significant mass gains can be made by reduction of the storage tank mass. Figure 4 illustrates the effect of storage duration on

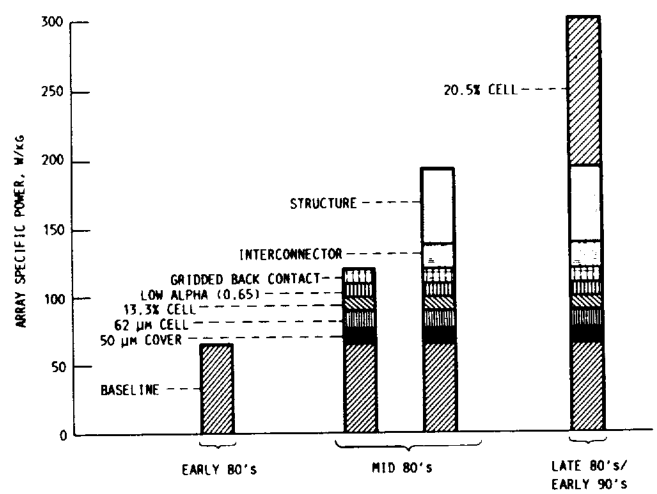


Fig. 3. High-performance solar array research and technology.

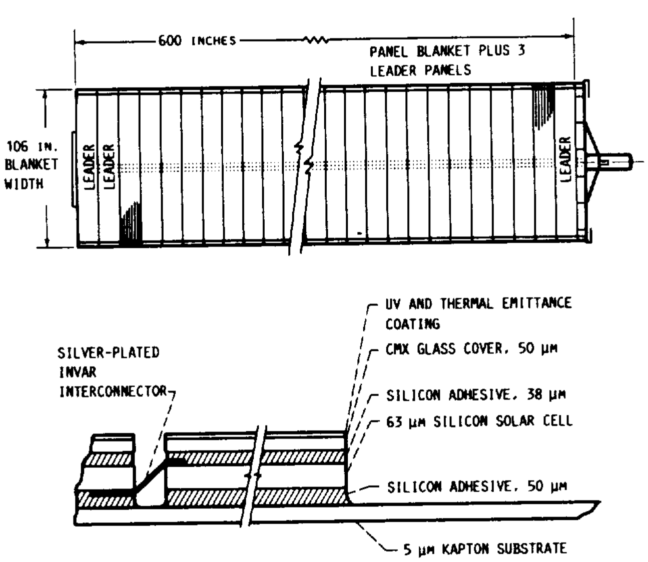


Fig. 2. Advanced photovoltaic solar array (APSA) wing and blanket.

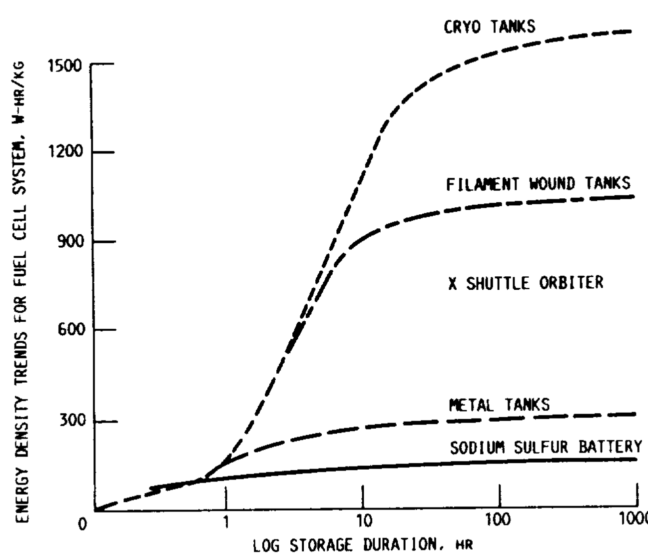


Fig. 4. Approximate energy density characteristic of fuel cell systems as a function of tank type and storage duration.

RFC system energy density for several tank types (L. H. Thaller, personal communication, 1988). For the high-pressure gas storage system chosen for the lunar base, the use of filament-wound tanks enables the storage system energy density to approach 1000 Whr/kg. This is exceeded only by cryogenic reactant storage, which at present has application for primary fuel cells only and is not viable for the lunar base mission.

SUMMARY

The development of an advanced photovoltaic power system that would have application for a manned lunar base is currently planned under the Surface Power element of Pathfinder. Significant mass savings over state-of-the-art photovoltaic/battery systems are possible with the use of advanced lightweight solar arrays coupled with regenerative fuel cell storage. The solar blanket, using either ultrathin GaAs or amorphous silicon solar cells, would be integrated with a reduced-*g* structure. Regenerative fuel cells with high-pressure gas storage in filament-wound tanks are planned for energy storage.

In conclusion, an advanced PV/RFC power system is a leading candidate for a manned lunar base as it offers a tremendous weight advantage over state-of-the-art photovoltaic/battery systems and is comparable in mass to other advanced power generation technologies.

REFERENCES

F.n J. C. C., McClelland R. W., and King B. D. (1984) GaAs cleft solar cells for space applications. In *Proceedings of the 17th Photovoltaic Specialists Conference,* pp. 31-35. IEEE, Piscataway, New Jersey.

Scott-Monck J. and Stella P. (1986) Advanced photovoltaic solar array program—A preliminary assessment. In *21st Intersociety Energy Conversion Engineering Conference, Vol. 3,* pp. 1458-1461. American Chemical Society, Washington, DC.

SOLAR WATER HEATING SYSTEM FOR A LUNAR BASE

N93-14005

Richard E. Somers and R. Daniel Haynes

REMTECH, Inc.
3304 Westmill Drive
Huntsville AL 35805

This paper describes an investigation of the feasibility of using a solar water heater for a lunar base. During the investigation, computer codes were developed to model the lunar base configuration, lunar orbit, and heating systems. Numerous collector geometries, orientation variations, and system options were identified and analyzed. The results indicate that the recommended solar water heater could provide 88% of the design load and would not require changes in the overall lunar base design. The system would give a "safe-haven" water heating capability and use only 7% to 10% as much electricity as an electric heating system. As a result, a fixed position photovoltaic array can be reduced by 21 m².

INTRODUCTION

Hot water will be needed at a lunar base for various sanitation requirements such as dishwashing, clothes cleaning, bathing, and food preparation. The environmental control and life-support system (ECLSS) will also require a continuous and significant amount of heat for processing waste water. Typical hot water usage temperatures range from 40°C to 80°C. Electric water heating using a photovoltaic or solar dynamic array can be expensive and inefficient and can require intensive maintenance. Another important goal is to prevent loss of equipment or life during an emergency by providing a "safe-haven." This is an independently operating portion of the base (typically the habitat module) to which the personnel can retreat. Electric water heating systems could require unacceptably high power levels from limited auxiliary power systems during an emergency.

To avoid these problems, a solar water heater similar to a terrestrial system is proposed (Fig. 1).

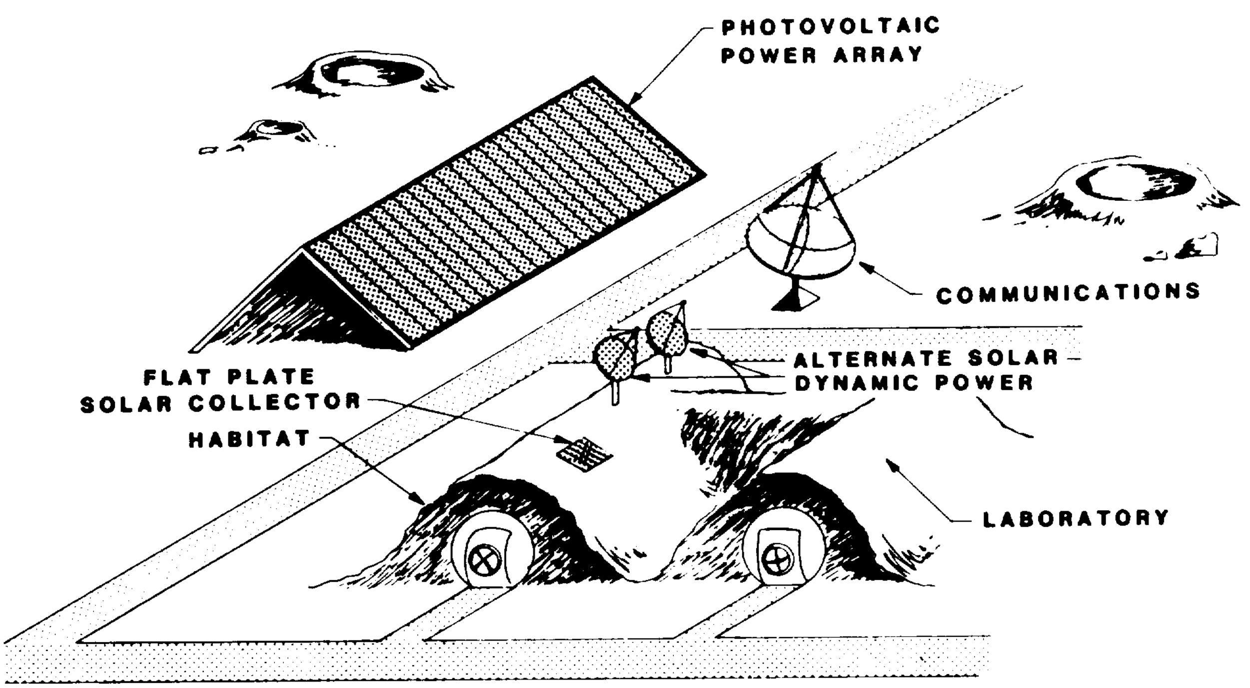


Fig. 1. Lunar base solar collector.

THERMAL MODEL

To investigate the proposed concept, computer programs were developed to assess the performance of candidate systems and the effects of system options. The external influences and internal processes of the lunar base are illustrated in Fig. 2 and listed in Table 1. TRASYS (*Jensen et al.,* 1977) was used to model the external effects, and a REMTECH program, QCOLL, written specifically for this purpose, was used to model the internal thermal processes.

External Influence Model

As indicated in Fig. 3, several types of collectors were modeled. A fixed position, flat plate collector and two types of variable position, concentrating or focusing collectors (dish and trough) were investigated. For reference during the investigation, the lunar base was modeled as two half-cylinders aligned east-west, similar to Fig. 2. The orientation of a collector to the sun determines the amount of incident energy. Obviously, the greatest incident energy occurs when the collector is perpendicular to the sun. In terrestrial applications, the collector must track the sun in two axes to obtain the maximum amount of energy because of daily and seasonal changes in the sun's position. For a lunar base, the situation is simpler because the Moon's equatorial plane is only tilted 1.5° to the solar ecliptic plane and therefore has no "seasons." By tilting a collector at an angle equal to the latitude of the lunar base, the collector can track the sun by rotating about only one axis during the lunar day. Traditional terrestrial applications, however, have shown that tracking the sun is unnecessary and that fixed position, flat plate collectors work well. Terrestrial applications have also shown that even when flat plate collectors are positioned relatively far from the optimal tilt and due south (northern hemisphere) azimuth, they still perform well. To determine effects of tilt and azimuth, the following cases were run

Case ID	Latitude	Tilt	Azimuth
L 000*	0°	0°	0°
L 400	45°	0°	0°
L 430	45°	30°	0°
L 440*	45°	45°	0°
L 434	45°	30°	45°
L 444	45°	45°	45°

* Denotes optimum condition for that latitude.

TABLE 1. External and internal parameters.

External Influences	Internal Processes
Configuration	*Collector*
• Shapes and position of collector and adjacent structures	• Type of system (plate or concentrator)
• View factors to adjacent	• Size
Orientation	• α and ϵ
• Orbital mechanics of Moon	• Pumped fluid or heat pipe
• Location, tilt, and azimuth on Moon	• Flow properties (rate, laminar flow)
• Angle of collector at any time to sun	• Piping size and material properties (κ, c_p, ρ)
Energy	• Heat balance (solar absorption-IR emission)
• Direct solar and albedo	*Storage*
• Direct and reflected IR	• Volume
	• Heat exchanger (pumped fluid)
	• Heat balance (solar energy added-energy to load)
	Demand Load
	• Time and duration of loads
	• Simultaneous multiple loads
	• Temperature of loads

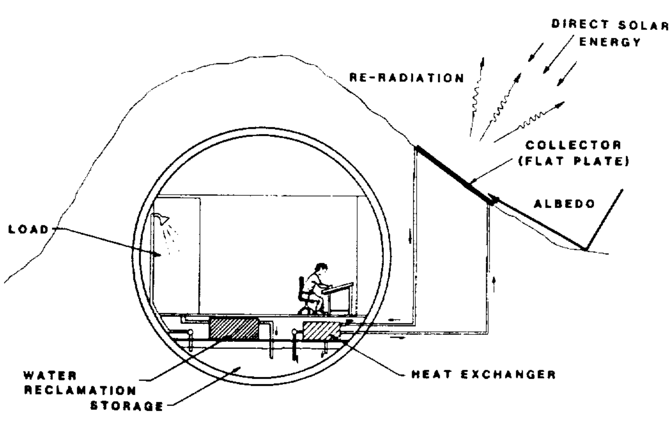


Fig. 2. External and internal conditions modeled.

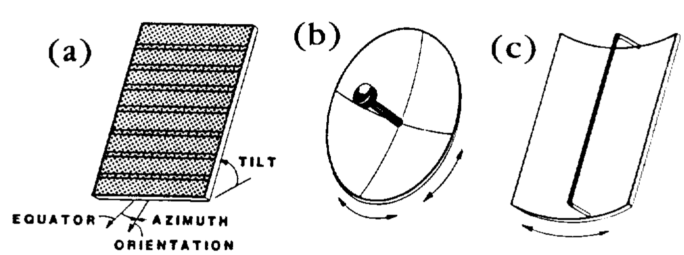


Fig. 3. Types of collectors modeled: **(a)** flat plate (pumped liquid or heat pipe; **(b)** two-axis tracking dish; **(c)** one-axis tracking trough.

The effect of tilt can be seen in Fig. 4 where the incident energy for each due south (0° azimuth) orientation is plotted. The plots start at lunar midnight, so no energy is received until approximately seven terrestrial days later. The incident energy increases until solar noon (approximately 14 days) and then decreases as the sun sets. For tilt, the worst case shown is the L 400 where the collector at a 45° latitude is flat on the surface. Approximately 60% of the ideal case incident energy is incident on this collector. By tilting the collector to 30° (L 430), the incident energy is increased and is only about 5% less than the optimum L 440. The optimum at 45° latitude, L 440, and the optimum at 0° latitude, L 000, are equal because they both have the same orientation to the sun.

Figure 5 shows the effect of azimuth. Here, the collectors pointed 45° to the east peak two to four days sooner and received 95% as much energy as the collectors pointed due south (northern hemisphere is assumed). It is seen, therefore, that the lunar fixed position, flat plate collectors follow the same trend as terrestrial collectors in that they collect energy at near optimum levels even when positioned considerably off the optimum tilt and azimuth.

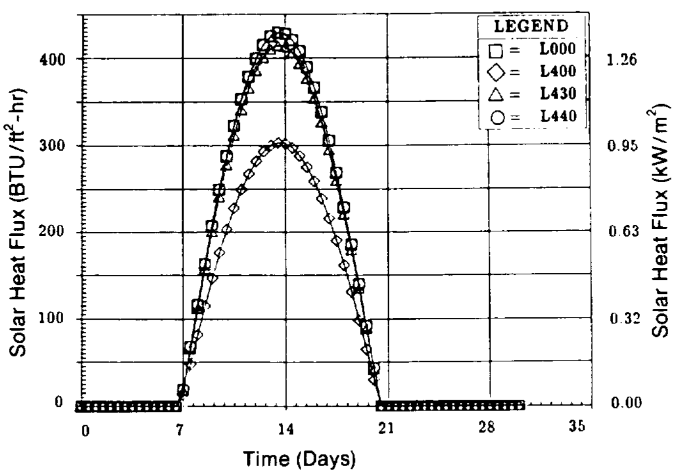


Fig. 4. Effect of collector tilt on incident solar energy.

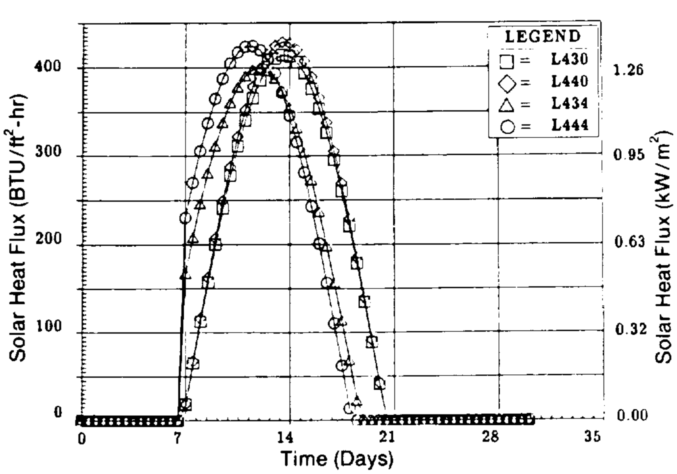


Fig. 5. Effect of collector azimuth on incident energy.

The incident energy for the dish and trough concentrators is constant, since they track the sun. Essentially, they receive the solar constant, 1352 W/m^2 (429 Btu/hr-ft^2) during the daylight hours, which is the maximum possible amount of solar energy available. The integrated total energy value is approximately twice that of the fixed position, flat plate at optimum orientation.

Internal Processes Model

The first step in modeling the internal processes was to establish the hot water usages and express them as a profile of the demand heating load. The plot shown in Fig. 6 is based on the loads shown in Table 2, which gives each assumed load and delivery temperature for an eight-person operation. These loads may change in the future, but the plot shown is the current estimate.

Two internally different collector systems were investigated and were modeled separately. The first, shown in Fig. 7a, uses a pumped liquid as the heat transfer medium. Since the liquid must not boil or freeze in the collector, the direct use of water was ruled out. Therefore, the liquid is pumped through a separate, collector/heat exchanger closed loop. In the meantime, water is pumped from storage through the heat exchanger and returned. The collector can be either a plate or a concentrator.

In the second system (Fig. 7b), the collector is a plate to which heat pipes have been attached. A heat pipe is a closed tube filled with a substance in its liquid and vapor phases. Heat on one portion of the tube evaporates the liquid and causes a higher vapor pressure in that portion. The vapor flows to the lower pressure areas of the tube where it is cooled and it condenses, thus perpetuating the low pressure. The liquid thus condensed flows by capillary action back to the heated region in small tubes placed in or under the heat pipe or meshes and grooves cut inside the heat pipe. In the heat pipe system model, the storage water is pumped from storage through a heat exchanger; this portion of the model coincides with the pumped fluid model.

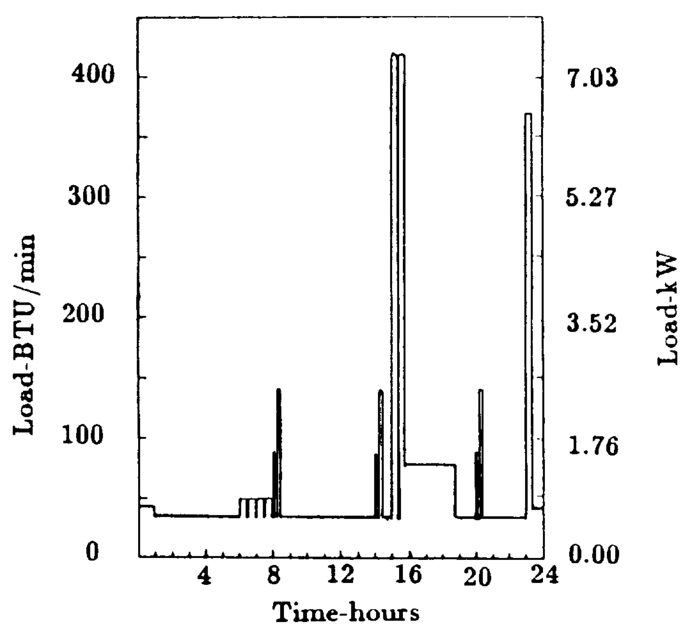


Fig. 6. Demand heating load.

TABLE 2. Individual demand loads for lunar base.

Demand	Occurrence	Amount	Time	Temperature
Handwashing[*,†,‡]	24	0.61 kg (1.35 lb)	1 min	41°C (105°F)
Showers[*,†,‡]	4	3.60 kg (8 lb)	18 min	41°C (105°F)
Potable[*]	3	6.89 kg (15.2 lb)	10 min	74°C (165°F)
Dishwashing[*,†]	1	43.50 kg (96 lb)	20 min	60°C (140°F)
Clothes Washing[*,§]	2	49.90 kg (110 lb)	20 min	66°C (150°F)
Dish Drying[§]	1	150 W	1.5 hr	38°C (100°F)
Clothes Drying[§]	1	750 W	3 hr	66°C (150°F)
Water Recovery[*]	Continuous	300 W		54°C (130°F)
Water Recovery[*]	Continuous	300 W		82°C (180°F)

[*] R. Bagdigion, personal communication.
[†] *ASHRAE*, 1984.
[‡] R. Garcia, personal communication.
[§] D. Schiller, personal communication.

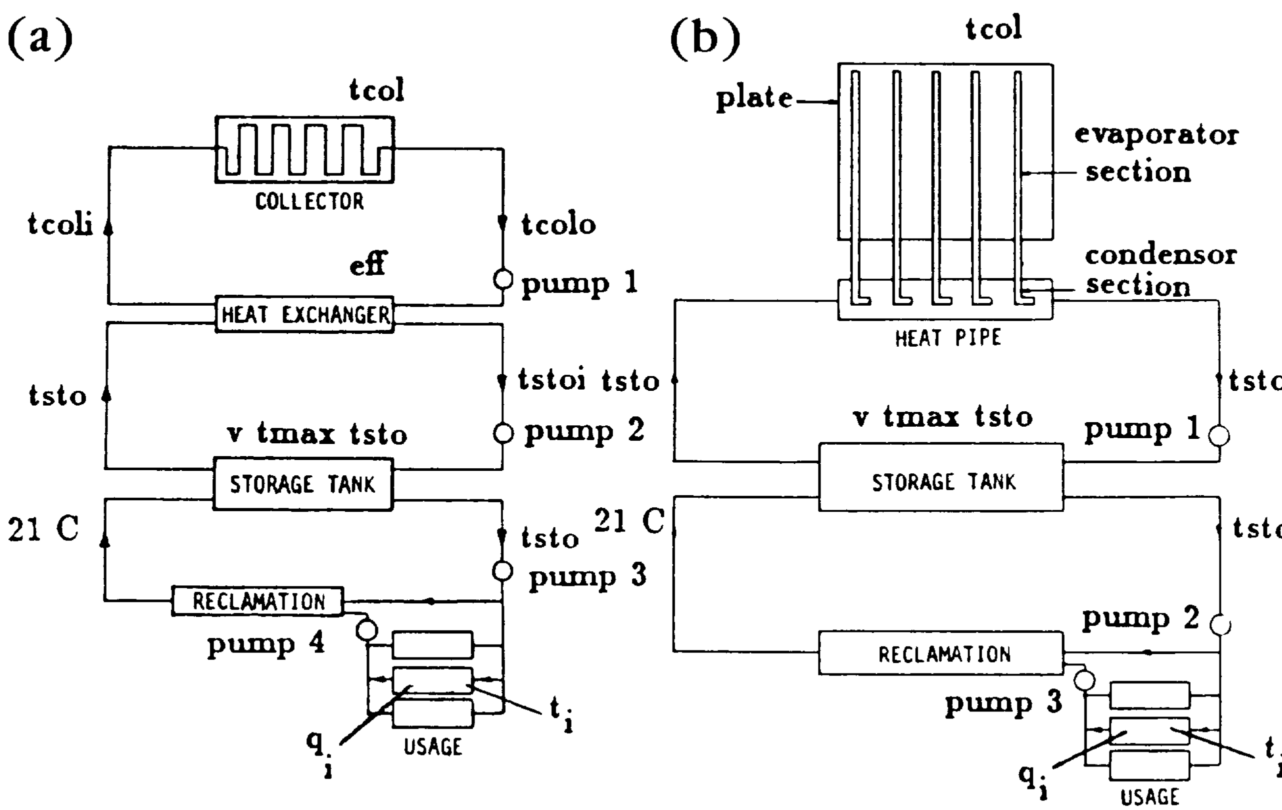


Fig. 7. System models for the internal processes: **(a)** pumped fluid or concentrator system; **(b)** heat pipe collector system.

The computer models for each system perform energy balances on all components at approximately two-minute intervals in the lunar day. Normally the run time simulated 1440 hr of activity on the lunar base. The first 720 hr allowed the system to reach steady state, and a normal operation cycle could then be observed for the second 720 hr. Generally, the pumps are predicted to run continuously during the lunar day (~14 terrestrial days). However, if the storage temperature becomes 93°C, the pumps are "turned off" by the model and excess heat reradiates to space.

PERFORMANCE

The methodology used for determining system performance and comparing options consisted of three steps. Initially, a baseline system was established. This was based on terrestrial experience and iteratively running the program for some of the options. A pumped fluid, flat plate collector system that heated 100% of the demand hot water with solar energy was chosen. Next, three variations of each option were simulated using the

appropriate computer model. In the final step, t_{sto}, SFT, η, and other parameters were compared to the baseline to determine whether the options being studied had a serious impact on system output.

Figure 8 is an example of a comparison between various values of α and ϵ. The t_{sto} was computed for the baseline ($\alpha = 0.80$, $\epsilon = 0.20$), for improved values ($\alpha = 0.96$, $\epsilon = 0.12$), and for a near-black body ($\alpha = 0.96$, $\epsilon = 0.96$). Note that in an ideal collector $\alpha = 1.00$ and $\epsilon = 0.00$, which means all energy is absorbed and none is reradiated. Only minor improvement is seen using the improved values, but a marked decline in t_{sto} and SFT is evident for the near-black body. The effect of all options is summarized qualitatively in Table 3.

Once the influence of each option was understood, no more work was done with those found to be negligible, and only the collector size and storage volume impacts were studied further. This study produced a series of "design curves" by which a designer can make quick trade-off studies.

Figure 9 shows the design curves for a pumped fluid collector. The SFT has been plotted as a function of collector area and storage volume. As expected, SFT increases as the collector size increases. This occurs regardless of the storage size up to ~2 m^2. The explanation for this phenomenon, which was seen in the design curves for all systems, is that the collector is too small to supply the total load. The collected energy is used almost immediately, leaving little or none to be stored; thus, little storage is required. Beyond the 2 m^2 point, additional energy is available after the demand has been satisfied; therefore, storage must be larger to accommodate it. If the collector size is increased beyond 4.5 m^2, little change occurs in SFT unless the storage volume is increased.

It can be seen that the storage volume is very large compared to the collector area. This large volume is required because of the exceptionally long night during which no solar energy is available to replace tank energy losses caused by water usage.

RECOMMENDED SYSTEM

To provide ~100% of the demand load with a solar system would require a minimum area of 4.5 m^2 (50 ft^2) of pumped liquid or heat pipe, flat plate collector, or 2.3 m^2 (25 ft^2) of dish or trough concentrator. Because the concentrators track the sun and thus could cause maintenance problems, and because the flat plate area is so modest, it is recommended that the flat plate be used. The heat pipe collector offers a major advantage in that a micrometeoroid strike would only rupture one of the heat pipes, but the others would continue to function since they are closed units. Rupture of a pumped liquid line would cause a shutdown of the entire system until the line was repaired. The heat pipes in a collector, however, must be carefully leveled horizontally to prevent a gravity gradient or they will not function properly. They also have a major disadvantage, since under no-load, high-solar input conditions they will boil, creating pressure that can burst the pipes. The pumped fluid system operates the same regardless of tube alignment and can be drained to avoid boiling or freezing. Therefore, the recommended system collector is a 4.5 m^2, pumped liquid, flat plate. The coating would have $\alpha = 0.80$ to 0.95 and $\epsilon = 0.10$ to 0.20.

To achieve ~100% solar contribution, our model predicts that the storage must contain a minimum of 30,000 l (8000 gallons) of water (Fig. 9). Although water may well exist as ice on the Moon (*Staehle,* 1983) or may be produced by burning hydrogen,

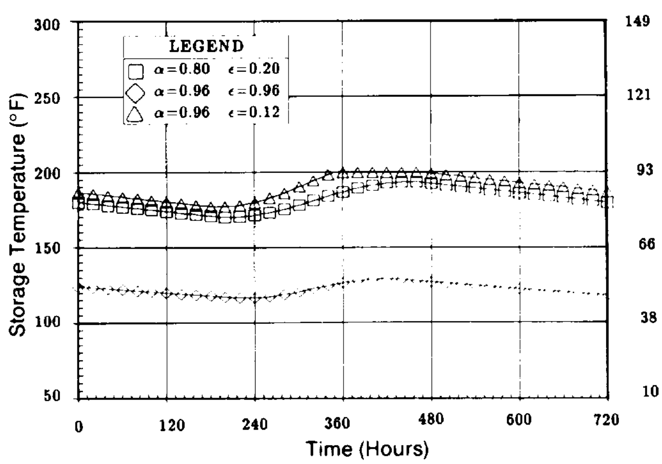


Fig. 8. Effect of absorptivity and emissivity.

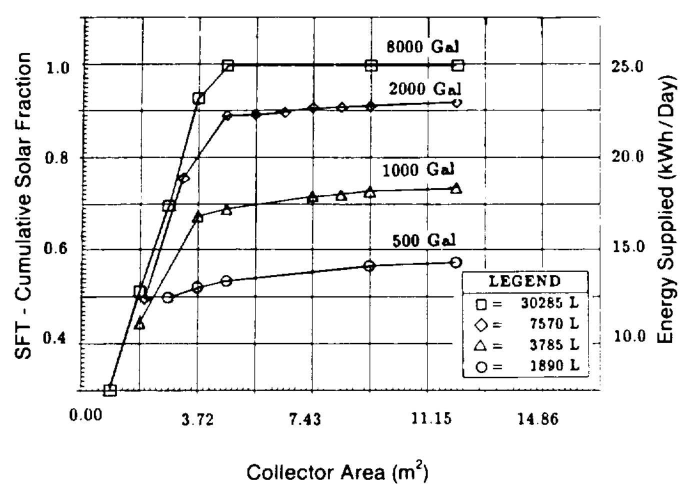


Fig. 9. Design curve for flat plate pumped fluid system.

TABLE 3. Effect of options on system performance.

Significant Effect	Negligible Effect
• Collector Size	• Fluid Type and Flow Rate
• Plate or Concentrator	• Collector Tilt and Azimuth (within 20°)
• Storage Size	• Heat Pipe or Pumped Fluid
• Coating α and ϵ	• Heat Exchanger Efficiency (within 0.5 to 0.8)

an initial eight-man base would probably not have this ability. The tank and water would have to be transported from Earth; therefore, 30,000 l of water and the tank for storing it are probably impractical due to cost. The model also predicts that if the storage volume is reduced by 75% to 7500 l (2000 gallons), the solar contribution only drops 12% (SFT = 0.88). This is still a large contribution for a modest-sized system, so the smaller volume is recommended.

The recommended system would have the following impact on delivery to and installation at the lunar base

Mechanical

Collector Area:	4.5 m^2 (10 cm thick)	Weight: 86 kg
Storage Volume: (See below)	7.6 m^3	Weight: 7557 kg
Auxiliary Equipment Volume:	0.2 m^3	Weight: 80 kg
Total Volume:	8.3 m^3	Total Weight: 7723 kg

Electrical

Total power to operate equipment: 175W
Coefficient of performance
(Useful Energy/Operating Energy): 10.5
Reduction of fixed photovoltaic array ($\eta = 10\%$): 21 m^2

The above assumes that no hot water storage was necessary before the addition of this system. This is not true, though the exact amount is not known. An estimate would be 760 to 1180 l (200 to 300 gallons). This amount should be subtracted from the impact of the system storage volume and weight, reducing them by 10% to 15%. Another consideration that partially offsets this large storage volume and weight penalty is that backup and stored electricity systems can be considerably decreased. The amount would be dependent on the type of electric storage system, but the reduction of weight and volume of fuel cells, for example, would be significant and make the solar system more attractive.

CONCLUSIONS

The thermal analysis has shown the following:

1. A heat pipe or pumped fluid flat plate collector of ~4.5 m^2 is well suited for satisfying up to 100% of the assumed hot water demand.

2. The volume of storage water required to allow significant solar contribution would be very expensive if transported from Earth.

3. A concentrator would need only 50% as much area as a flat plate; however, it could be more difficult to transport and maintain.

4. The size of the photovoltaic array and backup and electricity storage systems can be significantly reduced compared to an electric water heater.

5. Except for storage volume the system has only a minor effect on the base design.

The overall conclusion is that a solar water heater for a lunar base is feasible and even desirable.

NOMENCLATURE

c_p = Specific heat
eff = Heat exchanger effectiveness
k = Conductivity
q_i = Heat load required by ith device
SFT = Solar fraction total (heat supplied to load by solar energy/heat load)
t_{col} = Collector temperature
t_{coli} = Fluid temperature entering collector
t_{colo} = Fluid temperature exiting collector
t_i = Delivery temperature required by ith device
t_{max} = Maximum temperature of storage
t_{sto} = Water temperature in storage
t_{stoi} = Water temperature entering storage
V = Storage volume
α = Absorptivity in solar spectrum
ϵ = Emissivity in infrared (IR) spectrum
η = Thermal efficiency of system (heat supplied to load by solar energy/incident solar energy on collector)
ρ = Density

REFERENCES

ASHRAE (1984) *Handbook of Systems.*

Jensen C. L. and Goble R. G. (1977) *Thermal Radiation Analysis System II-TRASYS II User Manual.* Martin-Marietta Report MCR-73-105.

Staehle R. L. (1983) Finding 'Paydirt' on the Moon and Asteroids. *Aeronaut. Astronaut.*, 44-49.

AUTOMATION AND ROBOTICS CONSIDERATIONS FOR A LUNAR BASE

N93-14006

Nancy E. Sliwa[1], F. Wallace Harrison Jr., Donald I. Soloway, William S. McKinney Jr.[2], and Karin Cornils

MS 152D
Automation Technology Branch
NASA Langley Research Center
Hampton VA 23665-5225

William R. Doggett and Eric G. Cooper

Planning Research Corporation
Hampton VA 23665

Thomas E. Alberts

Computer and Electrical Engineering Department
Old Dominion University
Norfolk VA 23539-0496

INTRODUCTION

The development and use of advanced automation techniques can greatly enhance and, to some degree, enable the establishment of a permanent lunar outpost. This automation is currently classed in two groups by NASA's Office of Aeronautics and Space Technology (OAST): telerobotics, which is the remote computer-assisted manipulation of equipment and materials, and systems autonomy, which includes intelligent automated control, monitoring, and diagnosis. OAST is currently providing approximately $25M/year for the development and demonstration of telerobotic and system autonomy technology for NASA missions. This technology is being prepared for integration into current mainstream NASA operations including shuttle launch processing and mission control, the space station, and unmanned planetary mission control, so it can be assumed that much of this technology will be acceptable for use on the lunar surface.

An envisioned lunar outpost shares with other NASA missions many of the same criteria that have prompted the development of intelligent automation techniques with NASA. Because of increased radiation hazards, crew surface activities will probably be even more restricted than current extravehicular activity in low Earth orbit. Crew availability for routine and repetitive tasks will be at least as limited as that envisioned for the space station, particularly in the early phases of lunar development. Certain tasks are better suited to the untiring watchfulness of computers, such as the monitoring and diagnosis of multiple complex systems, and the perception and analysis of slowly developing faults in such systems. In addition, mounting costs and constrained budgets require that human resource requirements for ground control be minimized.

[1]Now at NASA Ames Research Center, Moffett Field CA 94035
[2]Now at Draper Labs, Cambridge MA

Activities on the lunar surface will require that automated systems deal with more uncertainty in their environment than will likely be found in preceding NASA missions. This uncertainty results from two sources: inability to precisely specify the working environment and decreasing precision in the hardware of the automated mechanisms from wear and exposure to the unfriendly lunar environment. A higher level of intelligence is required in the automated systems to successfully deal with this greater uncertainty.

A lunar outpost offers even more opportunities than earlier NASA missions for advancing the development of intelligent automated systems. A lunar base would offer more systems that are not life-critical, possibly allowing the expanded use of advanced automation techniques. That is, since many science, material processing, and other activities will be physically and mechanically remote from crew quarters, activity in these systems would not be as sensitive to crew safety concerns as in missions such as the space station. These systems would thus be excellent candidates for trial deployment of contemporary automation techniques, serving as testbeds for new technology. In addition, although many tasks of a lunar base are amenable to hard automation, it will not be feasible to provide a task-specific device for each. Flexible approaches to automation are required, in which a small set of adaptable devices can perform a wide range of tasks.

Much of the automation and robotic (A&R) technology necessary for a lunar base is expected to be available to NASA as a result of the space station A&R development and operations. However, all these technologies will require some degree of growth to accommodate the lunar environment, and certain specific problems will require unique solutions. The objective of this paper is to provide a glimpse of certain lunar base tasks as seen through the lens of A&R considerations. This can allow a more efficient focusing of research and development not only in A&R, but also in those technologies that will depend on A&R in the lunar environment. The goal is to make specific recommendations for designing lunar A&R systems and for areas of research focus.

A number of tasks that are expected to require A&R in a lunar base environment were considered. Estimates were made of the weight, volume, speed, and range requirements of the vehicle's mobility; the size, weight, and precision requirements of the parts handling; and the expected duration and frequency of these tasks. Using these tasks as realistic examples, certain general recommendations were determined for lunar A&R systems, and a hypothetical set of systems was developed for the considered tasks.

TASK ANALYSIS

Certain tasks that are expected to be necessary on a lunar base, and that are expected to require A&R technology, were provided to the Automation Technology Branch by the Langley Spacecraft Analysis Branch, based on their investigations of thermal, environmental, and transportation requirements for a lunar base. Each of these tasks could be accomplished in a variety of ways; many approaches might seem logical from an A&R viewpoint, but may not be suitable given certain other mission restrictions that are currently known. The optimal approach for each task must be determined by integrating A&R considerations with all other mission constraints. However, baseline approaches for each task were estimated as described below.

Soil mining, transportation, processing, and storage activities associated with liquid oxygen (LOX) production. It is assumed that the processing and storage activities will be accomplished with hard automation and the soil mining and transportation activities will be accomplished with intelligent automated vehicles. As a baseline approach, we accepted the assumption of a central mining vehicle serviced by several soil transportation vehicles. The mining operation will likely require a short-range mobile vehicle with some type of large, heavy, coarse-precision gathering capability. The soil transportation vehicles could be moderate-size and -range mobile vehicles with a mechanized soil hod; no manipulation would be necessary for the transportation vehicles. This is expected to be a continuous, long-duration activity.

Soil movement activities for site preparation and habitation (hab) module protection. Large-scale soil movement will be required for grading "roads" on the Moon, which would simplify both crew and autonomous vehicle movement between facilities. Additionally, hab modules will likely be covered with lunar soil as a barrier to radiation. Road grading requires large size and weight handling capabilities over a long range with only coarse precision. Module burying is similar but with only short-range requirements. Both these activities will be infrequent but intense, with most of it occurring at the initial establishment of the outpost and at specific intervals of expansion.

Hab module handling, transportation, and interconnection. This activity would require very large part-size/weight handling (if space station hab modules are used), with moderate precision. This activity will also be infrequent but intense, with most work of this type occurring at the initial establishment of the base and at specific intervals of expansion.

Exploration and core sample retrieval. Autonomous exploration can be handled several ways. If a highly competent and robust autonomous vehicle is available, such as the Mars Rover project hopes to produce, exploration can be continuous and last indefinitely, ranging over a large portion of the local environment. At the other end of the spectrum, autonomous exploration can be very limited, directed to specific spots of interest for short-duration missions, and can be under the detailed direction of the lunar crew or remote scientists. In either case, core sampling will require moderate size and weight capabilities over a long range, with moderate precision.

Crew/materials transportation. This would require a mobile vehicle with moderate size and weight capabilities over a long range, but probably no manipulation capabilities.

Remote experiment tending and inspection. This task is expected to require a mobile vehicle with moderate weight and size capabilities over a long range, with manipulation capabilities for light size and weight handling, with fine precision. This task is expected to be required only periodically, but for the life of the base.

Structural assembly. This is envisioned as the same type of strut-and-node assembly that will form the basis of the space station construction. Assemblies of this type will likely be built as protective covers for most of the lunar facilities. This activity would require small to moderate size and lightweight part handling over a short range, with fine precision. The duration and frequency of this activity depends on the priority of such protective covers and the rate at which new facilities are added. If protective covers are of high priority, or several new facilities are added simultaneously, this activity must be of continuous duration for a relatively short period of time. If such covers are on an as-possible basis, or if new facilities are added one at a time, gradually, then this activity can be intermittent and continue for a long time.

Solar and radiator panel installation and maintenance. This activity would require moderate size/weight part handling, with fine precision. Installation activities would be infrequent, with most of the work occurring at the initial establishment of the outpost and at specific intervals of expansion. Maintenance, repair, and replacement activities would probably be needed regularly but infrequently.

These task parameters are summarized in Table 1. The coarse estimates of the parameter values are shown in Table 2. These task scenarios and parameter values are working estimates only and are not to be taken as requirements definitions.

Note that these tasks deal primarily with external surface activities; self-contained internal automation, such as that required for attending enclosed plants and animals, maintaining crew modules, or processing specific materials, were not examined in detail. However, these activities could be expected to use specific automation technology developed for the space station or technology similar to that required for surface activities.

GENERAL TECHNOLOGY RECOMMENDATIONS

Based on these task parameter estimates and on the current state and rate of growth of required A&R technologies, general recommendations can be made for the use of certain approaches and technology to all lunar surface A&R systems.

Modularity

The first recommendation is obvious and well accepted in theory, but not generally well practiced. This is the concept of hardware and software modularity. That is, both hardware and software systems should be developed with isolatable, reusable modules. This will make maintenance of the systems much easier. Since the lunar surface is so harsh, hardware systems must be able to be regularly and easily maintained. Modules changed during

TABLE 1. Task requirement estimates.

	Mobility				Manipulation				Task	
Activities	Weight	Volume	Speed	Range	Weight	Size	Dexterity	Precision	Duration	Frequency
LOX Soil Gathering	heavy	large	slow	short	heavy	large	minimal	coarse	long	continuous
LOX Soil Transportation	moderate	moderate	moderate	moderate					long	continuous
Road Grading	heavy	large	slow	long	heavy	large	minimal	coarse	moderate	occasional
Hab Module Lifting	very heavy	very large	slow	short	heavy	large	minimal	coarse	short	seldom
Hab Module Transportation	very heavy	very large	slow	long					short	seldom
Hab Module Connection	heavy	large	slow	short	heavy	large	moderate	moderate	short	seldom
Hab Module Burying	heavy	large	slow	short	heavy	large	minimal	coarse	short	seldom
Exploration/Core Sampling	moderate	moderate	moderate	long	light	small	good	fine	long	frequent
Crew Transportation	moderate	moderate	moderate/fast	long					short	frequent
Materials Transportation	moderate	moderate	moderate	long					short	frequent
Remote Site Maintenance	moderate	moderate	moderate	long	light	small	good	fine	moderate	occasional
Structural Assembly	light	moderate	moderate	short	light	moderate	moderate	fine	moderate	occasional
Solar Panel Installation/Maintenance	moderate	moderate	moderate	short	light	moderate	good	fine	moderate	occasional
Radiator Pane Installation/Maintenance	moderate	moderate	moderate	short	moderate	moderate	good	fine	moderate	occasional

TABLE 2. Estimated parameter values.

Mobility		Manipulation		Task	
Weight		Weight		Duration	
Heavy:	>1 ton	Heavy:	>500 lb	Long:	>12 hr/session
Moderate:	500 lb < $\times$ < 1 ton	Moderate:	100 lb < $\times$ < 500 lb	Moderate:	1 hr/session < $\times$ < 12 hr/session
Light:	<500 lb	Light:	<100 lb	Short:	<1 hr/session
Volume		Size		Frequency	
Large:	>100 ft^3	Large:	>20 ft^3	Continuous	
Moderate:	20 ft < $\times$ < 100 ft^3	Moderate:	1 ft < $\times$ <20 ft^3	Frequent:	>1/day
Small:	<20 ft^3	Small:	<1 ft^3	Occasional:	1/day < $\times$ < 1/month
				Seldom:	<1/month
Speed		Dexterity			
Fast:	>10 mph	Good			
Moderate:	3 mph < $\times$ < 10 mph	Moderate			
Slow:	<3 mph	Minimal			
Range		Precision			
Long:	beyond local base site	Fine:	<1 mm tolerance		
Moderate:	within local base site	Moderate:	1 mm < $\times$ < 10 mm		
Short:	<100 ft	Coarse:	>10 mm tolerance		

routine maintenance could then be reconditioned, likely at the lunar base itself, for reuse. Likewise, the inevitable software maintenance will be simplified. Additionally, modularity will allow easier upgrades to accommodate new technology in both hardware and software.

Operability

The second recommendation is to provide both multimode and mixed-mode operability of the autonomous systems. Multimode operability means that a system, e.g., an autonomous vehicle, can be controlled by several different modes: (1) autonomously, (2) by an operator on site, and (3) by a remote operator, either from the crew modules or from Earth mission control. Mixed-mode operability indicates the existence of priorities and protocols to allow various control modes to work in concert. Both these mode capabilities are necessary for control of a lunar system.

In examining the need for multimode operability, consider that much of the work done by these systems will be repetitive and tedious. Additionally, there will be so many systems in simultaneous continuous operation that the lunar crew and Earth control will not have the resources or the desire to manually control or excessively monitor the systems. The systems must therefore be able to operate autonomously for extended periods of time.

On-site control is necessary to assist a crew member who may be on the lunar surface and have need of the system facilities, e.g., drive a vehicle somewhere other than its designated path. This mode may be critical for safety: a crew member may need to immediately override the other system control modes to protect either himself/herself or another crew member, the vehicle, materials, a facility, etc.

Remote operator control will likely be the most common alternative to autonomous control, and will be necessary to initiate, modify, or discontinue the activity of surface A&R systems. The majority of this control would come from lunar crew modules if the lunar base is manned, or from Earth control if the base is in an unmanned phase of man-tended operation. However, systems must be capable of control in either mode at any given time.

Given that multiple modes of control of a system are possible, the question is raised of which mode is in control at any given time. Mixed-mode operability deals with this question. Many situations are optimized by use of more than one mode simultaneously. For example, in manipulation tasks, the operator and computer can work concurrently, the computer doing the majority of the task, with the operator assisting at certain difficult junctures. Also, a lunar operator may request backup assistance from Earth control. However, protocols must be established to determine control mode priorities. For example, a human operator may be given priority over the autonomous mode at all times; an on-site operator may have priority over a remote operator in most circumstances.

Replication

The third recommendation is that there be maximum hardware and software replication and reuse. This means designing systems to be as similar as possible in both the software and hardware whenever multiple systems are necessary to perform a range of tasks. For example, the vehicle modules for systems to perform the "middleweight" tasks listed above could be identical, with fittings to accommodate different fixtures for different tasks: dexterous manipulator arms, a crew pod, a materials rack, a soil hod, etc. Likewise, the vehicle modules for the "heavy duty" tasks could be identical, and potentially similar to the vehicle mentioned above except on a larger scale.

Additionally, software structures and modules can be identical for many elements. For example, the operator interface may be identical for command, communication, and control of all systems. All autonomous vehicles may use the same navigation modules. Likewise, the internal software for self-monitoring and diagnosis may be structured similarly in all lunar surface systems. Besides facilitating development and maintenance, this approach would improve the crew learning and retention rate for these systems.

Although there may be an additional initial challenge in the design phase of these systems to maximize replication, this approach should significantly decrease manufacture and maintenance costs, and simplify the problem of maintaining both spare parts and expertise for maintenance. This recommendation is obviously heavily dependent on the first; replication of modules cannot be done if there is no modularity in the first place. NASA has attempted some use of system replication to decrease costs, e.g., the shuttle and the Mariner Mark II spacecraft vehicle. However, a lunar base offers an excellent chance to extend both the use of the concept and the potential savings in funds, time, and manpower.

Mechanisms

The type and form of hardware to be used for lunar systems must be the topic of much research. The severe dust problem and the continuing radiation exposure will require inventive design techniques combined with new materials to provide even a moderately reasonable level of mechanism endurance. But it is unreasonable to assume that complex mechanical systems can be made infinitely reliable for continuous operation on the Moon; systems must also be designed for easy maintenance. In early phases of the lunar base development, astronauts must be able to replace defective components and refurbish most parts themselves. In future phases, an automated "garage" can be envisioned, where maintenance and repairs to vehicles can be automatically performed based on computerized activity logs and fault scans. Vehicles could be automatically reconfigured based on dynamic task scheduling of ongoing and future activities.

In addition to easy maintenance, maximum functional redundancy should be a part of the entire set of lunar surface systems. Ideally, there should be sufficient functional flexibility in the automated systems to allow another vehicle to cover a necessary task if the primary vehicle is temporarily indisposed. At least initially, most functional redundancy may need to be accomplished by astronaut intervention.

Within this general framework of mechanism requirements, there are open questions relating to the best modes of transportation (wheeled, tracked, legged, suspended) for different systems and the manipulation requirements (how many arms, how many degrees of freedom, what size work envelope, etc.) of several different tasks. High-precision manipulation from a mobile platform, particularly in a low-gravity environment, must receive research attention. This type of mission analysis will require special simulation tools.

Sensors

Sensors are what make possible any significant degree of intelligent automation. Given the high degree of uncertainty in the lunar environment, tasks cannot expect to be fixtured and hard-automated as they currently are on the factory floor. Sensors allow automated systems to adapt to their uncertain and ever-changing environment and are an essential element for intelligent manipulation systems. Force/torque sensing and laser sensing will be very important to lunar surface systems; vision may be less important due to difficulties in adapting to lighting situations and speed requirements, though it will still be useful for providing essential operator information. Other less obvious sensors may be used very effectively on the lunar surface; e.g., "autonomous" navigation along routine paths could be achieved by using special beacons posted periodically along the desired path, with sensors on the vehicles designed specifically to detect the navigation signals.

Sensors within the mechanisms of automated systems are also essential to the diagnosability of faults in those systems. It will be essential to ensure that lunar systems are designed with sufficient sensor information available to allow fault isolation for repair.

Fault Detection and Recovery

Computers are well suited to the task of tirelessly watching for infrequent or slowly developing faults and for remembering the correct diagnosis and recovery sequences, even for rarely occurring problems. Humans are very poor at this type of task. Artificial intelligence has made major advances in the field of modeling and diagnosing sophisticated systems, making it possible to plan on the widespread use of this technology for lunar base systems. Such systems should be able to autonomously monitor all activity, diagnose failures, and recommend and/or perform recovery operations, allowing fault-scaled operations until full-scale repair can be performed, if necessary. Additionally, these systems should be able to monitor long-term performance, detect slowly developing problems, and recommend maintenance and repair activities to avoid future failure.

Design Knowledge Capture

Design knowledge capture (DKC) refers to the computerized maintenance of an "audit trail" for a system (both hardware and software) that records initial design, design changes, prototype development, bugs and fixes, production data and anomalies, and maintenance and repair; in other words, the life history of a particular system. This information is then available to facilitate maintenance and upgrades.

This technology has been designated by NASA as critical to many future missions. This technology is also of great interest to DoD and to commercial industry, particularly the auto industry. It is reasonable to assume that NASA can use components of this technology that will be developed by others, and extend the state-of-the-art in this technology with new applications and more stringent requirements, particularly for integration with other system components.

Computational Reliability

All the above recommendations assume that there will be sufficient sophisticated computing capability on board lunar surface systems. NASA and DoD currently have a major program for developing spaceborne multiprocessing and symbolic computers. Priority must be given to extending this capability for systems using multiple interacting processors, and to making the processor rugged enough for lunar surface travel.

The usefulness of computerized systems in the lunar environment will be directly proportional to the reliability of the processors and the software running in them. NASA Langley is currently seeking to improve the reliability-to-cost ratio of the validation and verification (V&V) of conventional systems. Additionally, NASA's AI community has given very high priority to mission-qualification techniques for knowledge-based systems. Research in this area needs to cover the broad spectrum of V&V, as well as field testing and acceptance procedures for knowledge-bases systems. This will include elements of completeness checking, safety and sensitivity analyses, and static and dynamic consistency tests.

VEHICLE SET

Given a task set and the above general recommendations, a hypothetical set of devices can be formulated for lunar surface work.

A key component of this set must be the mobility modules. One reasonable approach would be to provide two or three sizes of mobility modules: "smart platforms" (Fig. 1). A platform would include some standard set of actuators and sensors, a navigation module, an operator interface, a system executive, etc. At least a large platform (Fig. 1a) and a medium-sized platform (Fig. 1b) would be needed to accommodate the different tasks. These platforms would be identical in all but size.

Another approach is to use much smaller standard components, "smart wheels" (Fig. 2a), that can then be joined in series (Fig. 2b) and/or parallel (Fig. 2c) to create the size of platform needed for any particular task. This is a more intriguing but more complex approach, and would require significant advances in distributed system integration, control, and cooperation. However, this approach might ease logistics problems: small modules would be easier to pack and transport, and would allow at least some work to be done with a small number of "smart wheels." Heavier-duty capabilities could be added incrementally as more of these modules are brought in subsequent flights.

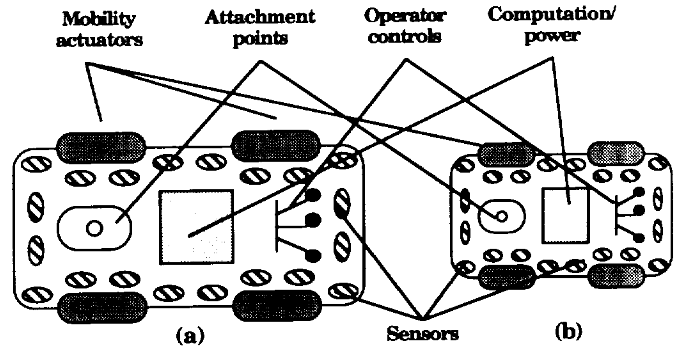


Fig. 1. Stylized renditions of the "smart platform" concept (top view).

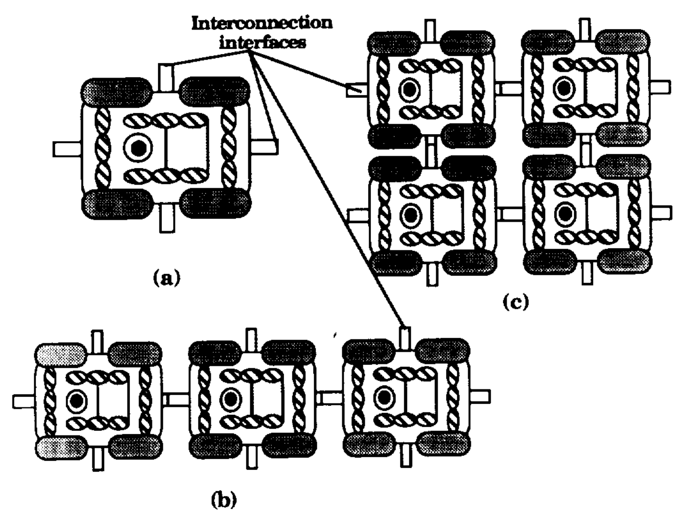


Fig. 2. Stylized renditions of the "smart wheels" concept (top view).

Given some standard mobility platforms, attachments can then be interchanged to adapt the platform to a variety of tasks. For example, a soil hod attached to a medium-sized platform could transport soil in mining operations. Manipulators on the same platform could do structural assembly and maintenance operations. Other attachments could adapt it to crew and material transportation.

Likewise, a large platform could accept attachments for soil mining, road grading, and large object lifting. It is possible that one attachment can perform several tasks.

It will also frequently be necessary to use more than one vehicle for any given task. For example, if a vehicle with manipulators is to perform a radiation panel installation task, the same vehicle should not be expected to be designed to carry radiation panels; a general-purpose materials-carrying vehicle should accompany the manipulator vehicle to the task site. Likewise, a vehicle for lifting heavy objects like hab modules may not have to carry them long distances; it may transfer its burden to a "train" of smaller vehicles for transportation.

AUTOMATION AND ROBOTICS PHILOSOPHY

It is also necessary to examine other scenarios for transportation requirements. For example, future phases of a lunar base could make extensive use of tunneling, as well as cable- or rail-driven vehicles. Anticipation of such future approaches could change the initial optimal A&R approach.

Even in the early phase of a base, suspended cable-driven apparatus may provide a very logical approach to many transportation needs. It takes advantage of the low lunar gravity, requires minimal equipment to be transported from Earth, is of relatively low complexity, and would be easy for astronauts to set up and reroute. Although this may seem like a low-automation approach to be advocating in this paper, it provides an opportunity to express a philosophy about an approach to lunar base automation. *A&R solutions to lunar base problems should be allowed to fill their proper niche at the proper time.* Properly applied, A&R can provide significant advantages: decreased costs, increased safety, and evolutionary development. Improperly applied, A&R can reverse these benefits, and saddle NASA with very costly yet unreliable and quickly antiquated systems.

The key to reaping the benefits of A&R lies in two areas: (1) focused research in A&R and supporting technologies, as listed above, and (2) a multidisciplinary approach to developing system requirements. A&R specialists cannot develop realistic systems based solely on sketchy knowledge of current and future mission constraints; likewise, A&R approaches cannot be developed, analyzed, and accepted or discarded without substantial knowledge of the many intricacies of the field. It is necessary to bring these two important elements, mission knowledge and A&R knowledge, together in a truly cooperative venture.

Acknowledgments. Our thanks to the Spacecraft Analysis Branch at NASA Langley Research Center, and to the Advanced Programs Office of NASA Johnson Space Center, for the information they have provided in support of this effort.

N93-14007

LUNAR SURFACE MINING FOR AUTOMATED ACQUISITION OF HELIUM-3: METHODS, PROCESSES, AND EQUIPMENT

Y. T. Li[1] and L. J. Wittenberg

University of Wisconsin-Madison
Wisconsin Center for Space Automation and Robotics
Madison WI 53706

INTRODUCTION

Helium-3 fused with deuterium is an attractive fuel cycle for nuclear fusion power reactors in the twenty-first century because it produces "clean" nuclear power (*Wittenberg et al.,* 1986) with no radioactive fuel or fusion product. Unfortunately, terrestrial resources of He-3 are scarce. Present assessments of both natural and man-made sources of He-3 indicate that a fusion plant of 500 MW electrical power could be fueled for only a few months.

In contrast, the surface of the Moon has a plentiful supply of He-3 (*Wittenberg et al.,* 1986). Helium-3, He-4, protons, and particles of other chemical elements formed from nuclear reactions in the sun have been implanted in the lunar regolith (soil) by the solar wind for the past 4 billion years. Due to constant meteorite impact, the grain size of the lunar regolith is extremely fine, which makes it an effective solar wind collector. The results of heating and degassing of lunar samples returned from the early Apollo missions (*Eberhardt el al.,* 1972) confirmed the presence of these solar wind particles. Although the concentration of these particles is low, the mass of the soil is large; consequently, the lunar regolith is estimated to contain more than a million metric tonnes of He-3.

The deuterium/He-3 fusion reactor yields 19 MW·yr (thermal) or ~10 MW·yr (electrical) per kilogram of He-3. The U.S.'s electrical power usage in 1987 was $\sim 3 \times 10^5$ MW·yr. The utilization of the lunar He-3 resource could provide, therefore, an energy source for the USA lasting for thousands of years. In addition, the lunar regolith contains other elements of the solar wind that are evolved during heating, such as hydrogen, nitrogen, and carbon compounds. Large amounts of these volatiles, which would be useful on the Moon as rocket fuel and life-support materials (*Bula et al.,* 1991) will be produced as by-products during the acquisition of He-3, as shown in Table 1.

Lunar maria regoliths rich in titanium are considered prime mining areas. This selection is made based on several considerations. First, maria regoliths are dominated by fine grain deposits. The energy of the solar wind particles is sufficient to implant them only a short depth into the surface of the grains. Therefore, the fine grains that have high surface-to-volume ratios have high concentrations of trapped particles. Second, the fine regolith in the maria extends to an average depth of ~3 to 10 m and grains containing solar wind particles have been retrieved from core samples up to 2 m deep (*Criswell and Waldron,* 1982). Third, it appears that regolith high in titanium is also high in helium content. High titanium regoliths are mostly derived from maria basalts (*Cameron,* 1991). Fourth, from an operational point of view, mining and processing maria regolith is relatively easier than dealing with rocks or the highland areas.

In this paper, we will present several techniques considered for mining and processing the regolith on the lunar surface. These techniques have been proposed and evaluated based primarily on the following criteria: (1) mining operations should be relatively simple; (2) procedures of mineral processing should be few and relatively easy; (3) transferring tonnages of regolith on the Moon

TABLE 1. Solar wind gas release predicted from mining of maria regolith.

Operation	Regolith (tonnes)	Concentration, ppm (g/metric tonne)				
		He-3	He-4	H_2	Carbon	Nitrogen
Surface Mining	1	$(6\text{-}13) \times 10^{-3}$	20-45	50-60	142-226	102-153
Beneficiate	0.45	$(5\text{-}11) \times 10^{-3}$	27	50	166	115
Gas Evolution	0.45	$(4\text{-}9) \times 10^{-3}$	22	43 (H_2) 23 (H_2O)	13.5 (CO) 12 (CO_2) 11 (CH_4)	4
Per kg He-3	1.4×10^5 (mined)	1 kg	3.1 tonnes	6.1 tonnes (H_2) 3.3 tonnes (H_2O)	1.9 tonnes (CO) 1.7 tonnes (CO_2) 1.6 tonnes (CH_4)	0.5 tonnes
Per Tonne Regolith into Heater	1 (beneficiated)	0.014 g	49 g	96 g (H_2) 51 g (H_2O)	30 g (CO) 27 g (CO_2) 24 g (CH_4)	9 g

[1]Now at Institute of Automation, Chinese Academy of Sciences, Zhong Guan Cun, Beijing, China

should be minimized; (4) operations outside the lunar base should be readily automated; (5) all equipment should be maintainable; and (6) economic benefit should be sufficient for commercial exploitation. We do not address the economic benefits in this paper; however, the energy benefits have been estimated to between 250 and 350 times the mining energy (*Kulcinski et al.,* 1988).

EVOLUTION OF SOLAR WIND GASES

Before a mining scenario could be proposed, we estimated the mass of regolith required to yield a specified amount of solar wind gases. For this scenario, we selected the continuous fueling of a 500-MW (electrical) fusion power plant that required 53 kg/yr of He-3. If the mining operation were conducted only during the lunar sunlit periods, ~4000 hr/yr, the He-3 production required is 13 g/hr. Next, we reviewed the experimental data for degassing of the regolith, selected the preferred temperature range for heating of the regolith and assessed the potential for beneficiation of the raw regolith.

Qualitative mass spectrographic analyses of the gases evolved during continuous heating of the Apollo 11 soils (*Gibson and Johnson,* 1971) indicated H_2 and He evolution began at ~200°C and was nearly complete by 800°C; CO and N_2 evolution began at ~600°C and continued to 1200°C; CO_2 was evolved between 700° and 1300°C; and H_2S and SO_2 evolution was initiated between 800° and 900°C. The evolution of H_2O and N_2 below 200°C was attributed to adsorbed terrestrial impurities. These soils contain no H_2O molecules; however, release of the embedded hydrogen atoms during heating apparently reduces some of the oxides yielding water that may constitute ~5% of the H_2 evolved above 200°C (E. K. Gibson, personal communication, 1987). The appearance of methane has not been confirmed but may constitute 5% of the total carbon. The condensation of the sulfur compounds SO_2 and H_2S from the evolved gas were observed (E. K. Gibson, personal communication, 1987) to contaminate the vacuum system with resinous products that were difficult to remove. For this reason, the proposed maximum heating temperature for the mining scenario was limited to the range of 700°-750°C so that the sulfur compounds would not vaporize.

Based upon the total yield reported (*Criswell and Waldron,* 1982) of solar wind gases evolved during the heating of Apollo 11 soils to ~1300°C (first line in Table 1), the average fine regolith on Mare Tranquillitatis was conservatively assumed to contain 30 ± 10 wt ppm of He-4 with a He-3/He-4 ratio of 400 atomic ppm. It was necessary, however, to estimate the amounts of the gases that would be evolved on heating to only 700°C. For this estimate, we used the mass spectrographic data by *Oró et al.* (1971) of gases evolved during the heating of Apollo 12 soils that reported the total yield of all gases evolved up to 750°C. We scaled these yields to 700°C and calculated the ratios between the yields of CO, CO_2, and N_2 as compared with the total yields from the regolith. These ratios were assumed, also, for the Apollo 11 samples. Quantitative yields of H_2 (*Carter,* 1985) and He (*Pepin et al.,* 1970) obtained during the step-wise heating of Apollo 11 samples as a function of temperature indicated that 86% of the He-3 and 84% of the H_2 would be evolved when the regolith is heated to 700°C. From this information the yield of each gas evolved per ton of raw regolith was determined based upon 100% recovery of the evolved gases (see Table 1).

In order to reduce the volume of regolith to be heated for gas evolution, the potential advantage of beneficiation of the raw regolith was investigated. Beneficiation based upon grain size is justified because the solar wind particles penetrate a short distance into the grains. Depth profiling measurements indicate that the He atom density peaks at ~20 nm below the surface but extends to a depth of 200 nm (*Waraut et al.,* 1979) and depends upon the "maturity" of the soil. Consequently, smaller particles have a higher gas-to-solid mass ratio as confirmed by analyses (*Hintenberger et al.,* 1970) and shown in Table 2. Unfortunately, the weight fractions per sieve size were not determined for these samples and had to be taken from another data source (*Criswell and Waldron,* 1982). When the gas analyses were combined with the size distribution of the raw regolith, the results in Table 2 indicate that the particles of <50 μm, which constitute only 47 wt% of the soil, yield 75% of the He, and particles less than 100 μm, which constitute 63 wt% of the soil, contain ~86% of the He. In addition, we noted for this case and other samples that the He content of the unsieved soil was ~30% higher than that obtained by the summation of the grain-size fractions. Apparently during the sieving process nearly 30% of the He was lost as a result of either agitation of the particles or as fine particles that may have become airborne. If this beneficiation system were enclosed in a gas-tight chamber, as it would be on the lunar surface, then this lost He would be captured and accounted for in the inventory of the smallest grain size. Based upon these observations, we estimated that the soil should be beneficiated

TABLE 2. Helium content as a function of regolith grain size.

Grain Size Fraction		He-3 Content*			
		10^{-5} cm^3 (STP)/g			
Sieve Size μm	Wt. Sample† %	Per grain size	Per sample	Frac/STD Sample %	Frac/Sample Corrected‡ %
-50	47.2	8.88	4.19	75	81
50-100	16.3	3.62	0.59	11	8
100-150	9.0	1.92	0.17	3	2
150-200	5.0	1.96	0.10	2	2
200-300	5.0	1.89	0.10	2	2
>300	17.5	2.48	0.43	7	5
TOTAL			5.58		
Unsieved Fines			7.44		

*Sample 10084 (*Hintenberger et al.,* 1970).
†*Criswell and Waldron* (1982).
‡ He-3 difference between original sample and sieved sample added to -50 μm sample.

to retain particles <50 μm, which would constitute ~45 wt% of the soil, but yield ~81% of the He contained in the bulk soil. Alternatively, the regolith could have been beneficiated to concentrate ilmenite particles, which constitute 10% to 30% of the regolith on Mare Tranquillitatis because selected samples containing high ilmenite fractions are reported (*Eberhardt et al.*, 1972) to contain up to 180 ppm of He. If the ilmenite were distributed uniformly in the soil, it would be more efficient to separate the ilmenite fraction; however, the local distribution of ilmenite is unknown. For this reason it was decided to beneficiate to retain the small particles of all mineral types.

The results of these analyses indicate that ~140,000 tonnes of regolith of average He-3 content must be processed to obtain 1 kg of He-3, but only 63,000 tonnes of the beneficiated regolith <50 μm needs to be heated for gas evolution (see Table 1). As a result, nearly ~1800 tonnes of regolith must be mined per hour to supply a 500-MW electrical power plant.

MINING STRATEGIES

Three strategic options for lunar surface mining and processing of regolith were considered, namely: (1) *in situ* volatilization of gases, (2) open-pit mining with central plant processing, and (3) mobile excavation-beneficiation-evolution followed by centralized volatile/isotopic separation. We will examine each of these mining options in the following scenarios.

IN SITU MINING

"*In situ* mining" proposes the extraction of the embedded volatiles without excavating the regolith. This system would consist of a mobile vehicle and an apparatus to direct thermal radiation or microwave energy onto the surface of the regolith. The escaping gas molecules would be collected in an enclosed gas-tight hood and pumped to a storage receiver (Fig. 1).

Unfortunately, *in situ* mining by applying concentrated sunlight is not practical because of the poor thermal conductivity of the regolith 0.09 to 0.13 mW/cm K (*Langsten et al.*, 1976) in the lunar environment. As a consequence, if the temperature of the surface were maintained at a constant 1000°C in order to avoid sintering, a simple calculation shows that five hours would be needed to raise the temperature at a depth of 1 cm to 600°C.

Penetration of heat can readily be gained by using microwave radiation. Some potential applications of microwave radiation to processing of lunar material have been studied (*Meek et al.*, 1985). Microwave radiation has been suggested as a method to heat lunar materials (*Meek et al.*, 1987), and experimental results from sintering lunar soil simulants using 2.45-GHz microwaves have been reported (*Meek et al.*, 1986). These studies have shown that the coupling of the regolith to the microwave radiation is considerably increased due to the defects in the material (*Bassett and Shackleford*, 1972), resulting from the cosmic ray and the intense impact events on the Moon.

To examine the feasibility of *in situ* mining using microwave, we conservatively took the loss tangent of the bulk regolith between 0.015 and 0.3 based on the electrical data of the lunar samples (*Strangway et al.*, 1972). Loss tangent characterizes the coupling between the substance and the microwave radiation, and is temperature dependent, as shown in Fig. 2a (*Cheng*, 1983). A plane wave was assumed to radiate perpendicularly to the surface for the estimation purpose. As the microwave penetrates the regolith, the strength of its electrical field attenuates and decreases to 1/e at a depth d, the "depth of penetration." For example, at a fixed frequency of 2.45 GHz, the depth of penetration is a function of the loss tangent and, therefore, a function of temperature, as shown in Fig. 2b. As the field of the microwave is

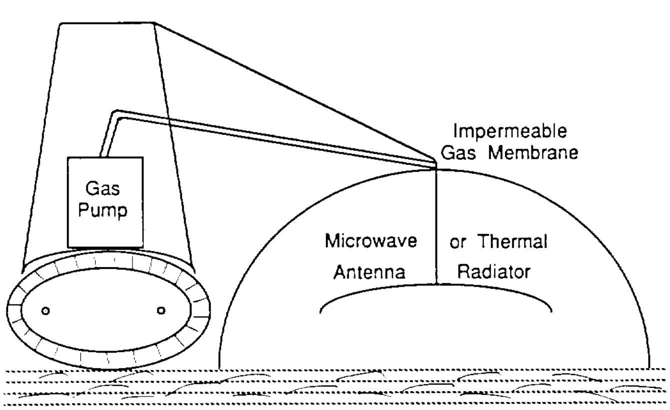


Fig. 1. Sketch of an *in situ* gas evolution device using either solar thermal energy or microwave radiation.

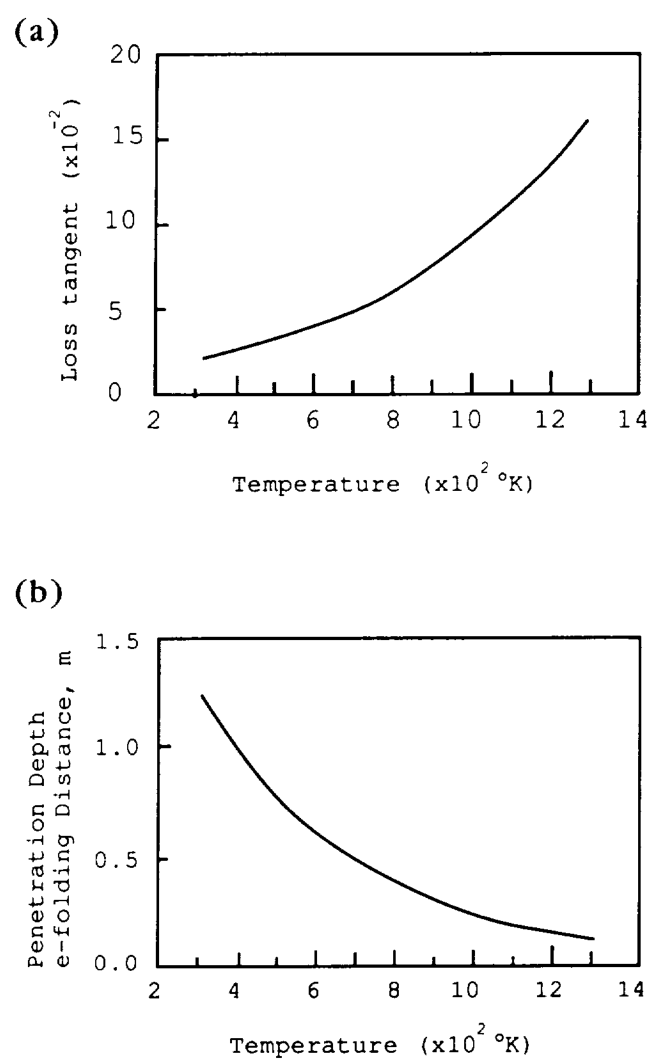


Fig. 2. **(a)** Loss tangent and **(b)** penetration depth-e-folding distance, as functions of temperature at 2.45 GHz radio frequency.

attenuated, the energy is dissipated and used to heat the regolith, changing the temperature profile. The changed temperature profile in turn alters the attenuation distribution.

To calculate how much helium would be emitted by the heating mechanism described above, we used the data obtained by a stepwise heating of the lunar fines returned by the Apollo 11 mission (*Pepin et al.,* 1970). The initial temperature distribution was assumed uniform at 250 K, approximately the temperature of the regolith at a depth of >30 cm. The frequency of the microwave and the intensity of the electrical field were 0.5 GHz and 400 V/m, respectively. The 0.5-GHz frequency was used instead of the conventional 2.45-GHz frequency because the depth of penetration at 2.45-GHz frequency is approximately 30 cm at low temperatures and decreases as the temperature of the regolith rises, which makes it difficult to heat the regolith at >0.5 m depth in a reasonable time. A typical set of the results by computer simulation are shown in Figs. 3 and 4. Figure 3 shows the temperature profile at 475 sec (7.75 min) when the surface reaches 1000°C, the sintering temperature of the material, and Fig. 4 shows the rate of evolved He-3 per m^2, by which the total yield of 25.0 cm^3 (STP)/m^2 He-3 was obtained. Finally, the total amount of microwave energy input into the regolith was 3.6 GJ.

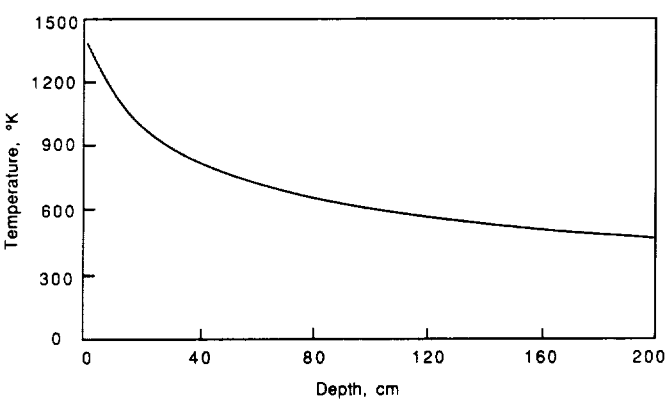


Fig. 3. Temperature profile in the regolith as a function of depth after microwave heating for 475 sec at a frequency of 0.5 GHz and an electrical field of 400 V/m.

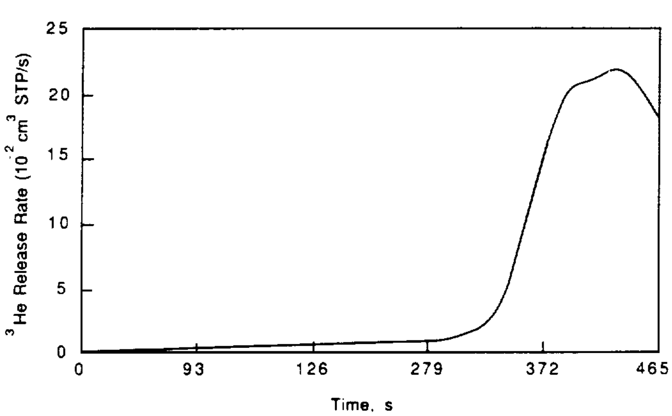


Fig. 4. He-3 release rate from the regolith as a function of heating time for the temperature profile shown in Fig. 3.

The excessively high microwave energy required is mainly due to the intrinsic nature of the method because no boundary is provided to confine the microwaves as well as the regolith. As a result, only the top layers of the regolith are heated sufficiently to release trapped volatiles and large amounts of energy are wasted on heating of the deeper regolith; consequently, the energy efficiency is <3%.

In addition, another major concern of this mining method is that the volatiles escaping from the regolith would scatter isotopically instead of rising toward the surface; consequently, a large portion of the emitted gas would not be collected. We are led to conclude, therefore, that the regolith must be excavated and heated in an enclosure.

A MOBILE MINING SCENARIO

In order to select the preferred mining scenario, the entire flow chart for He-3 recovery must be considered (Fig. 5). The process (on the right) begins with a type of open-pit mining technique in which the regolith would be placed on conveyor belts and transported to a central processing facility, as is traditionally done for terrestrial mining. At the end of the process the "tailings," which have the same mass as the original regolith but are of greater volume unless compacted, must be discarded, preferably into the original mine pit. Large volumes of the regolith must be lifted and handled in order to produce a useful amount of He-3. The area needed to be mined consists of ~1.8 km^2/yr if the mining trench is 2 m deep and the soil bulk density is 1.8 to 2.0 tonnes/m^3. As a result, the lengths of the conveyor belts from

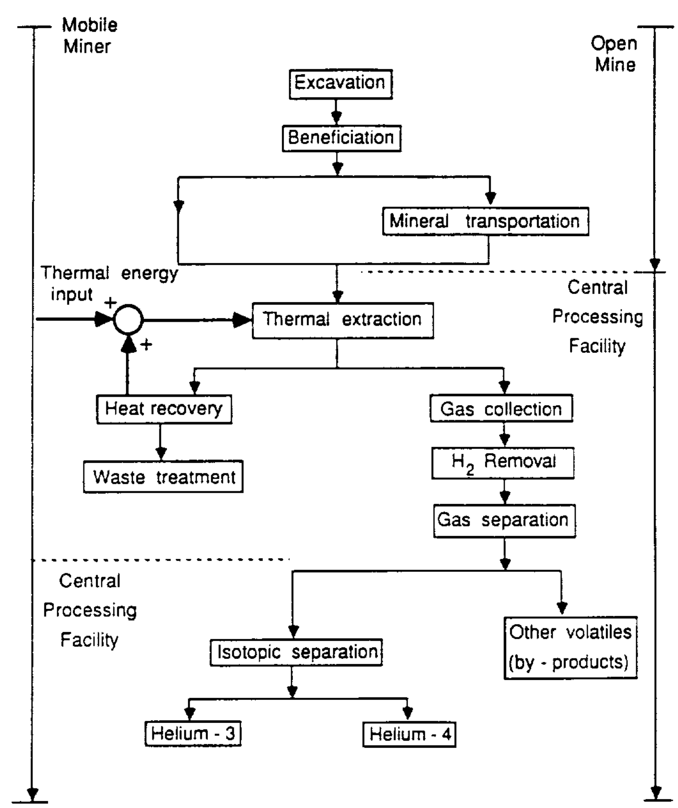


Fig. 5. Excavation, beneficiation, and thermal gas extraction systems integration required for the mobile miner concept, left, or the open mine-central processing facility, right.

the mine to the central processing plant increase rapidly each year when significant quantities of He-3 are needed. Also, additional conveyor belts are needed to return the processed regolith to the open pit.

Because of the large flow of regolith in the open-pit concept, a mining scenario based upon the use of a mobile miner was suggested. Such a mobile mining system consists of a bucket wheel excavator at the front followed by a series of mobile modules (see cartoon sketch in Fig. 6). Each module performs a single or multiple processing function(s) such as excavation, beneficiation, preheating, main heating, gas extraction, and heat recovery. Mobility is independently provided to each module. Mineral flow is handled by lifting conveyors, which are mounted to the modules. Gas-tight enclosures may be placed around each conveyor, if needed. The whole assembly moves at the rate of 23 m per hr, excavating a trench 20 m wide. In addition, it can be quickly moved from one mining site to another as a unit, or individual modules can be recalled to the lunar base for maintenance or replacement as required.

The task of excavating maria regolith on the Moon is akin to strip-mining sand and gravel on the Earth. Of course, the lunar environment is quite different from the terrestrial one and has been viewed as an obstacle to the operation of machinery. On the other hand, studies of lunar bases and other activities have constantly shown that the demand for some form of mechanical systems must be used for these enterprises. Consequently, we believe that the use of mechanical operations may be minimized, but not eliminated. The successful operation of three lunar rovers during the Apollo program suggests that sustained operation of mechanical devices is possible (*Morea,* 1991).

The bucket wheel excavator (BWE) appears to be the most useful for the purpose of removing the top 2-5 m of regolith. The BWE has multiple buckets mounted on the circumference of a rotating wheel and takes progressive sideward and upward cuts of the mineral as the wheel is slewed and rotated, respectively. The mineral scooped into the buckets is then discharged onto a conveyor belt when the buckets are moved to their top positions. The excavator is usually mounted on crawlers, providing mobility. This excavating method is advantageous over other systems because (1) this method provides a continuous supply of minerals, particularly favorable when the mining rate is high; (2) the effective output of a single BWE ranges from several hundred to several thousand cubic meters per hour on the terrestrial base, and if this output capability can be maintained on the lunar base, a single excavator can match the need for a power plant of 500 MW electrical output; (3) the BWE is physically compact and has a low mass-to-product ratio, which is desirable in regard to the transportation of equipment from Earth; and (4) the entire machine can be returned to a lunar base for maintenance.

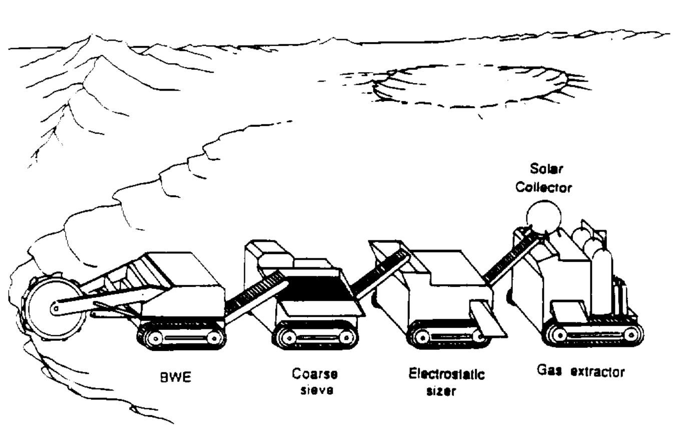


Fig. 6. Conceptualized mobile mining arrangement. Units could be combined into one vehicle.

PROCESSING REGOLITH

Mineral processing to produce the end product, He-3, consists of three operations: beneficiation or grain size selection, heating the beneficiated regolith, and the recovery and separation of the volatiles. Our major concerns in this respect have been the feasibility study of the technology involved and the energy consumption in the processing.

After the regolith has been elevated from the surface, it is first subjected to the beneficiation process, by which the finer portion of the mineral is selected and the coarser portion is rejected. As discussed earlier, grains of $<50\ \mu m$ retain ~81% of the He but constitute only 45 wt% of the regolith so that the energy required for heating the regolith is reduced. Technically, beneficiation may be done initially by a coarse sieve followed by an electrostatic sizer. Electrostatic separation of lunar minerals requires further research (*Inculet,* 1987) and testing because pristine grains of the fine regolith in the lunar environment may tend to agglomerate and the distribution of agglutinates in the raw soil is ill defined.

The subsequent major step of processing is the heat treatment, by which the beneficiated fines are thermally activated in order to release the trapped solar wind elements that are bound within the surfaces of the grains. As previously discussed, the heating will be limited to 700°-750°C. Of prime consideration is the thermal energy required to heat the regolith. If the fines $<50\ \mu m$ are retained, then the heater must process 800 tonnes/hr. Based upon the heat capacity of the regolith, ~1 J/g·K, and the need to heat the regolith from 250 to 973 K, the thermal power required is ~160 MW. In order to reduce this energy requirement, nearly 90% of the energy is conserved by the use of solid-to-solid recuperators by which the heated regolith emerging from the heater transfers its thermal energy to the incoming regolith. These heat recovery units are connected by heat pipes, as shown in Figs. 7 and 8; however, the design, construction, and testing of these recuperators require further development. If the recuperators operate successfully, only ~16 MW of thermal energy is needed. This energy could be conveniently supplied during the lunar day by the use of six solar energy collectors, 50 m in diameter, focused upon receivers attached externally to the heater. These solar reflectors are large by terrestrial analogies; however, the lunar environment of one-sixth gravity and the absence of wind-loading should simplify their construction. Perhaps aluminized plastic sheets stretched over light-weight metal frames would suffice. The reflectors must track the sun and the miner, but both move slowly.

We propose three schemes to heat large tonnages of regolith in a closed system to capture the emitted volatiles. The first scheme uses the concentrated solar energy to heat a medium such as liquid lithium in heat pipes, as shown in Fig. 7, or He-4 (by-product) in a cycling loop. The heat transfer medium brings the heat to layers or cells of preheated regolith in the main heater. The main heater is divided into layers or heating cells because the thermal conductivity of the regolith is small; however, it may be 5-10 times better than for the regolith on the lunar surface,

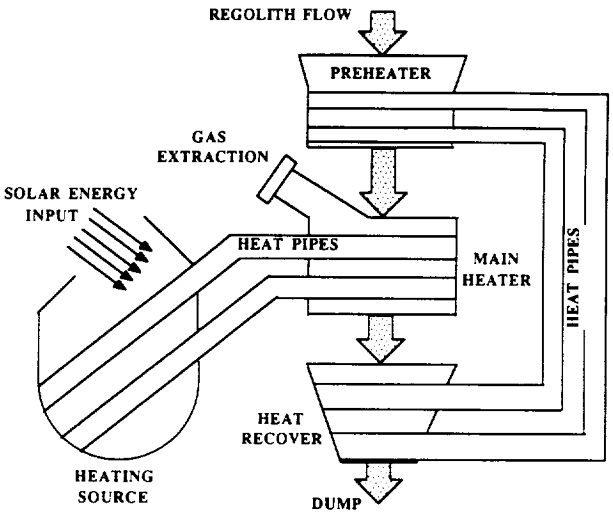


Fig. 7. Arrangement for the use of solar thermal energy to heat regolith fines in an enclosed oven.

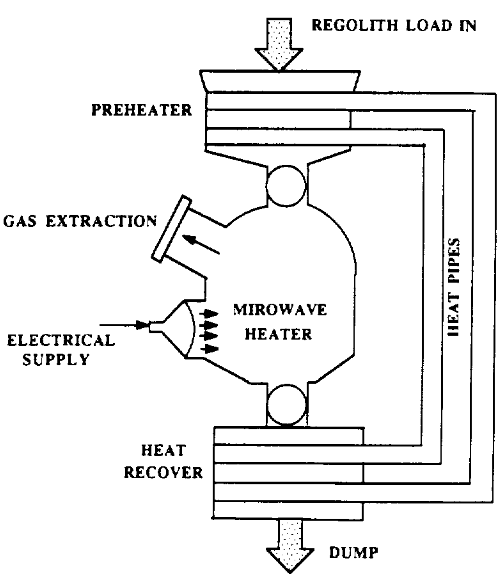


Fig. 8. Arrangement for the use of a microwave heating technique to process regolith fines.

because the existence of the emitted gases inside the chamber increases the heat transfer coefficient. The size of the gaps between the cells is large enough to allow the dry regolith to flow easily. As an example, for a heating chamber 2.5 m high, 10 m wide, and 19.4 m long, with half the volume occupied by 400 tonnes of regolith preheated to 300°C in gaps 2 cm wide, and the temperature of the heating medium at 850°C, the temperature rise of the full 400 tonnes reaches 600°C in 17 minutes.

The second heating scheme employs microwaves as the energy source for the heating process. The electrical source of the microwave generator may be supplied by either a solar-to-electrical energy converter or a nuclear power plant. As shown in Fig. 8, the microwave energy launched by antenna and reflected in all directions inside the oven strongly couples with the regolith providing essentially a bulk heating. Consequently, the temperature of the load will increase much faster, yielding a higher rate of processing Moreover, the equipment can be simpler as it is essentially a resonant cavity. Gravitational flow of the fines in the cavity is sufficient. These features make this scheme appealing. The disadvantage of this scheme is that it requires an electrical energy supply and the efficiency of generating microwave energy from electricity is about 50%. Low solar-to-electrical energy conversion, ~20%, would also be involved if solar photovoltaic devices provided the electrical energy source; consequently, it would be more energy efficient, requiring fewer solar collectors, if the solar thermal energy could be used directly.

AN ADVANCED FLUIDIZED BED REACTOR AND HYDROGEN REMOVAL SYSTEM

The third heating scheme considered uses a "fast-moving" fluidized bed reactor. In such a reactor the beneficiated regolith particles are introduced near the vented floor of the reactor and are levitated and transported to the top of the reactor in a heated gas stream. At the top of the reactor the particles and the gas are separated in a cyclone separator, as shown in Fig. 9. For particles <50 μm with a density of 3.2 g/cm^3, the terminal velocity of the particles in the lunar gravity is 3.7 cm/sec in a hydrogen gas stream at 0.5 MPa (5 atm) pressure (*Zhang and Yang,* 1986). The gas velocity must be greater than the terminal velocity in order to levitate the particles and somewhat greater in order to transport the particles vertically. Because the terminal velocity is so low in the lunar gravity, the gas velocity was increased to seven times the terminal velocity, yielding a particle velocity of ~22 cm/sec. These parameters permitted a volume density of 10% solid particles in the gas phase and a particle flow rate of 2 g/cm^{2}sec or 60 kg/sec for a 2-m diameter reactor (*Yerushalmi and Avidan,* 1985).

Laboratory analyses of the evolution of solar wind gases are normally conducted in a vacuum apparatus, while a sweep gas is proposed here. An important consideration for such gas emission from a surface is whether the gas pressure of the emitted species surrounding the solid is sufficiently high to increase the back reaction, namely resolution of the gaseous species in the solid. With the high gas velocity and turbulent flow of the particles within the bed, a high concentration of He surrounding the particle is unlikely. Another consideration for diatomic gas molecules, such as H_2, is that two H atoms must recombine on

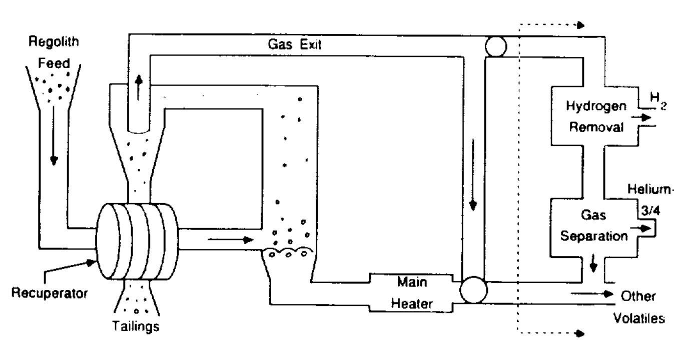


Fig. 9. A fluidized bed technique for heating regolith fines with continuous removal of the evolved gases.

C-4

the surface before the molecule can escape to the gas phase. Certain foreign gases adsorbed from the gaseous phase may retard the formation of H_2, for instance. In the case of He, however, it effuses as a single atom and, therefore, chemical interferences at the surface should not retard He evaporation. These proposed mechanisms will need experimental verification.

The circulating gas will be heated to ~750°C by use of solar energy. The regolith particles will be preheated so that they will be quickly heated by the gas. For a heat transfer coefficient of 300 W/m^2K from the gas phase to the solid, the center of the particle reaches ~700°C in 0.1 sec. Of concern, however, is the time required for the implanted solar wind gases to diffuse from the particles. The diffusion rate for He atoms in this material has not been determined and may depend upon the migration of bubbles because of the low solubility of He in the ore. Such measurements have been made for the diffusion of radioactive hydrogen (tritium) from Li_2SiO_4 and indicate that the H atom diffusion coefficient D is very small, $\sim 4 \times 10^{-11}$ cm^2/sec at 700°C (*Werle et al.,* 1986). During regolith degassing analyses, the evolution of He and H_2 is similar; therefore, the use of $D(H_2)$ may be acceptable for D(He). The approximate time, t, for the bulk of the solar wind particles to diffuse from regolith particles can be estimated from the relationship, $t = \Delta^2/D$, where D = the diffusion coefficient and Δ = the depth of the gas atoms, ~0.2 μm. This relationship indicates ~10 sec is required for H atoms and the other solar wind particles to diffuse from the particles. Because of the required diffusion time, the particles must be kept in the heated gas stream for 10 sec, while moving vertically at 22 cm/sec; therefore, the height of the fluidized bed reactor (FBR) should be 2.2 m. The FBR parameters are listed in Table 3. For a 2-m-diameter FBR, four FBRs would be needed to process the regolith at the required rate of ~800 tonnes/hr.

Vacuum locks will be required at the entry and exit ports of the reactor. Sliding seals and door apparatus such as currently used on pressurized coal combustion furnaces (*Goidich,* 1986) will be used so that nearly continuous feed rates can be maintained. The exit lock must be capable of evacuation before the regolith is ejected to the lunar surface. The amount of evolved solar wind gases that may adhere to the regolith is unknown; however, some experimental information indicates that this quantity should be small. *Holmes et al.* (1973) found that the surface area of the fine regolith decreased significantly after heating between 500° and 600°C. In addition, they found that H_2O adsorption, caused by terrestrial water, appeared to open the structure of the regolith and increase the surface area. Their results imply that the adsorption of nonpolar molecules, such as H_2 and He, on the degassed regolith should be very small. The adsorption of the highly polar molecule H_2O would be greater; however, only small amounts of H_2O are formed during the high temperature degassing of the regolith so that its potential effect upon increasing the surface area should be very small.

TABLE 3. Parameters for the fluidized bed reactor.

FBR Parameters	
Size of reactor	2 m diameter × 2.2 m high
Gas pressure	0.5 MPa (5 atm)
Gas velocity	0.26 m/sec
Particle velocity	0.22 m/sec (in lunar gravity)
Particle residence time	10 sec
Regolith flow rate	60 kg/sec
He-3 yield	13 g/hr
Reactors required	4

The gas stream is continuously circulated through the main heater and then returned to the reactor. A side-stream is diverted from the main gas stream in order to collect the evolved solar wind gases. The flow to this side stream equals the rate of gas evolution and has a volume composition of 72% H_2, 18% He, and 10% other gases. The high H_2 concentration must be reduced in order to eventually liquefy the He; consequently, most of the H_2 is removed from the gas stream at this stage by the technique of permeation through thin-walled, 1.27 mm outside diameter, palladium-silver alloy tubes (*Ackerman and Koskinas,* 1972). The gases are cooled to 300°C for this process and the H_2 concentration is reduced to ~5% in the He stream at the exit of this diffuser (see Table 4). Nearly 2500 Pd tubes are required for the diffuser, but they can be placed into a cylinder only 0.2 m in diameter because of their small size. This diffuser can, therefore, be carried easily on the mobile miner. The pure H_2 from the diffuser is then compressed and stored in large gas cylinders that are periodically transported to a hydrogen storage depot.

The He and other gases, Co, CO_2, N_2, and a trace of H_2, upon exit from the nonpermeate stream of the diffuser, can also be compressed and stored in gas cylinders ready for transportation to a central gas processing facility.

TABLE 4. Parameters for the hydrogen diffuser.

Tube material	Palladium alloy
Tube dimensions	o.d. = 1.27 mm; wall = 0.13 mm; length = 24 m
Number of tubes	2500
Tube bundle dimensions	0.2 m i.d. × 24 m length
Operational temperature	300°C
Operational pressure on tube	i.d. = 700 kPa (7 atm) o.d. = 19 kPa (0.19 atm)
Inlet gas composition (mole %)	72 H_2; 18 He; 10 other gases
Exit gas composition (mole %)	5 H_2; 61 He; 34 other gases
Permeate gas flow rate	4.2 millimoles H_2/sec · tube

CENTRAL GAS PROCESSING FACILITY

Pressurized gas cylinders containing the solar wind gases are transported to a central gas processing facility. This facility contains a variety of gas separation systems that are needed to separate and purify each of the gaseous components and finally to isotopically separate the helium isotopes. Some of this separation equipment may require specialized auxiliary items and analytical instrumentation. Also, the composition of the gases may vary as various ore bodies of the regolith are mined requiring changes in the purification schemes. For these reasons, such separation equipment is better utilized at a central facility rather than being attached to each miner unit.

The separation equipment will be similar to that found in commercial chemical operations, such as chemical getters for absorption of hydrogen; selective adsorbers, such as molecular sieves, for the adsorption of H_2O and CO_2; selective permeation barriers, which have recently become commercially available (*Haggin,* 1988); and temperature-controlled liquefaction equipment. The liquefaction process will require large radiator surfaces because radiation is the only method to dissipate heat on the lunar surface; consequently, liquefaction is used sparingly as a separation process. Liquefaction could be expeditiously accomplished during the long lunar night when the surface temperature decreases to ~102 K, or if operated during the lunar daylight, the radiators must be shaded. Ultimately, all the helium isotopes must be

liquefied to <4 K for isotopic separation. Numerous techniques have been developed for helium isotopic separations; however, cryogenic techniques are preferred. A cryogenic refrigerator will be needed, therefore, to operate between the liquid helium reservoir and the radiator temperature.

Partial separation of the helium isotopes at the lunar facility is needed due to the observation that the gases evolved from the regolith have a He-4/He-3 ratio of ~2500:1. The transportation system for delivery of the He from the Moon to Earth either as a gas or as a liquid has not yet been conceptually designed. In either form, however, very large amounts of inert He-4 would be transported for each small quantity of He-3. Such delivery would only be economical if a large terrestrial market developed for He-4.

The first stage of the He isotopic separation process would consist of a "superleak" apparatus (*Listerman and Watkins*, 1970) utilizing a filter with very fine pores. Superfluid He-4 flows through this filter when it is cooled below the lambda temperature, 2.2 K. Conversely, liquid He-3 is a normal fluid at this temperature and does not flow through the filter, but becomes enriched on the feed side of the filter. Such a technique has been proposed (*Wilkes*, 1978) to enrich He-3 from <1 ppm in He-4 up to ~1%. Because this technique functions effectively regardless of the gravitational environment, it would be useful on the Moon. At a concentration of ~1% He-3, the solution would be transferred to a cryogenic distillation apparatus for purification to 99+% He-3 (*Wilkes*, 1973). The characteristics of operational distillation columns change in low gravity environments because they rely upon density differences of solutions refluxing on the column (*Pettit*, 1985); consequently, at a particular enrichment value of He-3, yet to be determined, the final purification, may be more effectively accomplished after its delivery to Earth.

CONCLUSIONS

Several methods, processes, and equipment types have been surveyed to provide for the recovery of He-3 and other solar wind particles from the lunar regolith. A mobile mining scheme is proposed that meets most of the mining objectives. This concept uses a bucket-wheel excavator for excavating the regolith, several mechanical and electrostatic separators for beneficiation of the regolith, a fast-moving fluidized bed reactor to heat the particles, and a palladium diffuser to separate H_2 from the other solar wind gases. At the final stage of the miner the regolith "tailings" are deposited directly into the ditch behind the miner and cylinders of the valuable solar wind gases are transported to a central gas processing facility. During the production of He-3, large quantities of valuable H_2, H_2O, CO, CO_2, and N_2 are produced for utilization at the lunar base. For larger production of He-3 we recommend the utilization of multiple-miners rather than increasing their size. Multiple miners permit operations at more sites and provide redundancy in case of equipment failure.

Acknowledgment. This work is supported by the NASA Office for Commercial Development of Space.

REFERENCES

Ackerman F. J. and Koskinas G. J. (1972) A model for predicting the permeation of hydrogen-deuterium-inert gas mixtures through palladium tubes. *Ind. Eng. Fundam., 11,* 332-338.

Bassett H. L. and Shackleford R. G. (1972) Dielectric properties of Apollo 14 lunar samples at microwave and millimeter wavelengths. *Proc. Lunar Sci. Conf. 3rd.,* pp. 3157-3160.

Bula R. J., Wittenberg L. J., Tibbitts T. W., and Kulcinski G. L. (1992) Potential of derived lunar volatiles for life support. In *The Second Conference on Lunar Bases and Space Activities of the 21st Century,* this volume.

Cameron E. N. (1992) Mining for helium—Site selection and evaluation. In *The Second Conference on Lunar Bases and Space Activities of the 21st Century,* this volume.

Carter J. L. (1985) Lunar regolith fines: A source of hydrogen. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 571-581. Lunar and Planetary Institute, Houston.

Cheng D. K. (1983) *Field and Wave Electromagnetics.* Addison-Wesley, Reading, Massachussetts. 300 pp.

Criswell D. R. and Waldron R. D. (1982) Lunar utilization. In *Space Utilization, Vol. 2* (B. O'Leary, ed.), pp. 1-53. CRC Press, Boca Raton.

Eberhardt P., Geiss J., Graf H., Grögler N., Mendia M. D., Mörgeli M., Schwaller H., Stettler A., Krähenbühl, and von Gunten H. R. (1972) Trapped solar wind noble gases in Apollo 12 lunar fines (12001) and Apollo 11 breccia (10046). *Proc. Lunar Sci. Conf. 3rd,* pp. 1821-1856.

Gibson E. K. Jr. and Johnson S. M. (1971) Thermal analysis—Inorganic gas release studies of lunar samples. *Proc. Lunar Sci. Conf. 2nd,* pp. 1351-1366.

Goidich S. J. (1986) Developing the turbocharged pressurized fluidized bed combustion boiler. *Heat Eng., 52,* 100-107.

Haggin J. (1988) New generations of membranes developed for industrial separations. *Chem. Eng. News, 66,* 7-18.

Hintenberger H., Weber H. W., Voshage H., Wänke H., Begemann F., and Wlotzka F. (1970) Concentrations and isotopic abundances of rare gases, hydrogen and nitrogen in lunar matter. *Proc. Apollo 11 Sci. Conf.,* pp. 1269-1282.

Holmes H. F., Fuller E. L. Jr., and Gammage R. B. (1973) Interaction of gases and lunar materials: Apollo 12, 14 and 16 samples. *Proc. Lunar Sci. Conf. 4th,* pp. 2413-2423.

Inculet I. I. (1987) *Electrostatic Mineral Separation.* Research Study Press, Letchworth, England.

Kulcinski G. L., Sviatoslavsky I. N., Santarius J. F., Wittenberg L. J., Cameron E. N., Crabb T. M., and Jacobs M. K. (1989) Energy requirements for helium-3 mining operations on the Moon. In *Proc. Fifth Symposium Space Nuclear Power Systems,* pp. 77-82. Orbit Books, Malabar, Florida.

Langseth G., Keihm, S. J., and Peters K. (1976) Revised lunar heat-flow values. *Proc. Lunar Sci. Conf. 7th,* pp. 3143-3171.

Listerman T. W. and Watkins R. A. (1970) Superfluids separations. In *USAEC Rpt., MLM-1529,* pp. 40-45. U.S. Govt. Printing Office, Washington, DC.

Meek T. T., Vaniman D. T., Cocks F. H., and Wright R. A. (1985) Microwave processing of lunar materials: Potential applications. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 479-486. Lunar and Planetary Institute, Houston.

Meek T. T., Vaniman D. T., Blake R. D., and Cocks F. H. (1986) Electromagnetic energy applied to and gained from lunar materials. Symposium '86, Sept. 22-24, Pitman, New Jersey.

Meek T. T., Vaniman D. T., Blake R. D., and Godbole M. J. (1987) Sintering of lunar soil simulants using 2.45 GHz microwave radiation (abstract). In *Lunar and Planetary Science XVIII,* pp. 635-636. Lunar and Planetary Institute, Houston.

Morea S. F. (1992) The lunar roving vehicle—Historical perspective. In *The Second Conference on Lunar Bases and Space Activities of the 21st Century,* this volume.

Oró J., Flory D. A., Gibert J. M., McReynolds J., Lichtenstein H. A., and Wikstrom S. (1971) Abundance and distribution of organogenic elements and compounds in Apollo 12 lunar samples. *Proc. Lunar Sci. Conf. 2nd,* pp. 1913-1925 .

Pepin R. O., Nyquist L. E., Phinney D., and Black D. C. (1970) Rare gases in Apollo 11 lunar material. *Proc. Apollo 11 Lunar Sci. Conf.,* pp. 1435-1454.

Pettit D. R. (1985) Fractional distillation in a lunar environment. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 507-518. Lunar and Planetary Institute, Houston.

Strangway D. W., Chapman W. B., Olhoeft G. R., and Carnes J. (1972) Electrical properties of lunar soil dependence on frequency, temperature and moisture. *Earth Planet. Sci. Lett., 16,* 275-281.

Waraut M., Kiko J., and Kirsten T. (1979) Microdistribution patterns of implanted rare gases in a large number of individual lunar soil particles. *Proc. Lunar Planet. Sci. Conf. 10th,* pp. 1531-1546.

Werle H., Abassim J. J., Breic M., Clemmer R. G., Elbel H., Häfner N. E., Masson M., Sciers P., and Wedemeyer H. (1986) The LISAI experiment: In situ tritium release investigations. *J. Nucl. Mater., 141-143,* 321-326.

Wilkes W. R. (1973) ^{3}He-^{4}He distillation apparatus. *USAEC Rpt., MLM-2005,* pp. 1-15. U.S. Govt. Printing Office, Washington, DC.

Wilkes W. R. (1978) Helium-3 recovery and enrichment technology. In *USDOE Rpt., MLM-2419,* pp. 102-105. U.S. Dept. of Energy, Washington, DC.

Wittenberg L. J., Santarius J. F., and Kulcinski G. L. (1986) Lunar source of He-3 for commercial fusion power. *Fusion Technol., 10,* 167-178.

Yerushalmi J. and Avidan A. (1985) High velocity fluidization. In *Fluidization,* 2nd edition, pp. 274-289. Academic, New York.

Zhang J.-Y. and Yang G-L. (1986) Determination of the optimum gas velocity for dilute phase transport of coarse particles in large vertical tubes. In *Circulating Fluidized Bed Technology* (P. Basu, ed.), pp. 221-227. Pergamon, Toronto.

THE LUNAR ROVING VEHICLE—HISTORICAL PERSPECTIVE

N93-14008

Saverio F. Morea

Research and Technology Office
NASA Marshall Space Flight Center
Huntsville AL 35812

As NASA proceeds with its studies, planning, and technology efforts in preparing for the early twenty-first century, it seems appropriate to reexamine past programs for potential applicability in meeting future national space science and exploration goals and objectives. Both the National Commission on Space (NCOS) study and NASA's "Sally Ride study" suggest future programs involving returning to the Moon and establishing man's permanent presence there, and/or visiting the planet Mars in both the unmanned and manned mode. Regardless of when and which of these new bold initiatives is selected as our next national space goal, implementing these potentially new national thrusts in space will undoubtedly require the use of both manned and remotely controlled roving vehicles. Therefore, the purpose of this paper is to raise the consciousness level of the current space exploration planners to what, in the early 1970s, was a highly successful roving vehicle. During the Apollo program, the vehicle known as the Lunar Roving Vehicle (LRV) was designed for carrying two astronauts, their tools, and the equipment needed for rudimentary exploration of the Moon. This paper contains a discussion of the vehicle, its characteristics, and its use on the Moon. Conceivably, the LRV has the potential to meet some future requirements, either with relatively low cost modifications or via an evolutionary route. This aspect, however, is left to those who would choose to further study these options.

INTRODUCTION

Dreams of exploring the universe and traveling in space to other worlds and planets probably go back to the days of Copernicus when he pointed out that the Earth was not the center of the universe. With the subsequent technical and mathematical efforts of the early scientists such as Galileo, Kepler, and Newton, man became more aware of the universe and the laws that govern its motions. Thus, from the naive dreams of early man wrapped in legends and myths, modified by better physical and scientific understanding, man came to the realization of the possibility of flight into space. Indeed, the foundation for the investigation of space was laid through this inauspicious beginning.

The history of the LRV may have begun in the world of science fiction that had as its roots this evolving notion that man was only a part of a much larger unvierse. In 1901 for instance, the Polish science fiction writer Jersz Zulawski wrote *NA Srebrnym Globie (On a Silvery Globe)* in which his space travelers, after landing on the Moon, used a roving vehicle to perform a traverse that began at the lunar North Pole and proceeded south through Mare Frigoris and Mare Imbrium, ending near Mare Vaporum and the lunar equator—a very ambitious traverse. It then became a relatively short step from the science fiction writers of the nineteenth and twentieth centuries to the first primitive steps in the accomplishment of man's dream of visiting other worlds.

HISTORY AND BACKGROUND

The evolution of the LRV, from the fiction of these early visionaries to the nonfiction of contemporary engineers and scientists, proceeded via a series of more pragmatic contractor and government studies conducted primarily during the 1950s and 1960s. It was during this period of time when dreams, blended with creativity and technology, sparked with the national objective of "landing a man on the Moon in this decade," gave initial life to what was to become a reality in the 1970s: driving a car on another planet. To discuss all the various concepts and studies performed and how these concepts finally led to the design of an LRV would take far too long and would not be particularly relevant to the objective of this paper. However, it should be mentioned that numerous studies were conducted by organizations such as Boeing, Bendix, Lockheed, General Motors, Northrup, and Grumann, just to name a few. These studies examined configurations of vehicles that included fully automated designs with lunar life times of a year and a range of 1000 km, manned configurations of four and six wheels, tracked vehicles, manned flying platforms, mobile laboratories containing a shirt-sleeve environment for the astronauts, small automated rovers the size of a suitcase, and machines the size of a bus.

The LRV was not initially part of the early Apollo planning by NASA, but rather evolved into the agency's planning during the mid-phases of the program. As the milestone of sending a man to the Moon before the end of the decade of the 1960s became more realistic with each successful Apollo test flight in near-Earth orbit, and the expected safety margins for the subsequent missions began to more clearly emerge, plans that would maximize the scientific return from the Moon began to take on more significance in NASA's planning. In other words, once the task of satisfactorily testing the basic Apollo hardware was demonstrated, NASA's plans for optimizing the return on investment from subsequent missions to the Moon came into clearer focus.

In late May of 1969, the agency planning for an LRV culminated in a decision to proceed with development of a light article two months prior to the first manned lunar landing (Apollo 11). Subsequently, the responsibility for the management of the design and development of the LRV was given to the Marshall Space Flight Center in Huntsville, Alabama, and in turn to this author. After open competition during the summer of 1969, followed by competitive negotiations with the Bendix Corporation and the Boeing Company, NASA awarded a contract to the Boeing

Company on October 29, 1969. The contract, among other things, called for the delivery of a "manned qualified" flight vehicle to Kennedy Space Center (KSC) for installation into the Apollo 15 spacecraft by March 1971. The first flight article delivery was to take place a mere 17 months from contract go-ahead, only 22 months from NASA's decision to proceed with the progam. Because relatively little was known about the conditions on the lunar surface when the LRV program was initiated, a significant technical challenge faced not only engineers who established the technical design requirements, but also the engineers who were to design, test, and build this marvelous "spacecraft on wheels." To accomplish this task with a technically sophisticated and reliable vehicle in such a short period of time and within extremely tight budget constraints, new and innovative approaches to the procurement and management aspects of the program were required. Given the constraints the program was faced with, it is probably correct to say that no other program has replicated or surpassed the track record of this one. However, the procurement and management aspects of this program are another study in itself.

With the benefit of 20/20 hindsight, the justification and need for the LRV may seem unassailable today, but such was not the case at the time that the go-ahead decision had to be made. Remember, the crew of Apollo 11 had not yet landed on the Moon. Reserving 400 to 600 lb of payload to carry a car to the Moon did not find favor among some NASA officials, who would much rather have carried this additional payload as extra "hovering" fuel for the lunar module (LM). The extra fuel would have provided more assurance that a safe place to land on the Moon could be found, thus decreasing the risk that the mission would have to be aborted at a most critical moment and just short of the principal objective. The decision to proceed, therefore, was a brave one to make at that particular time and not, by any means, a unanimous one within NASA.

The other side of the equation, however, dealt with how much more science could be accomplished if the astronauts had a relatively fatigue-free mode of transportation. The use of the LRV not only increased the distance the astronauts could explore away from the LM, but also substantially impacted how long the astronauts would be able to remain outside the LM. For instance, the Apollo 11 crew only traveled about 250 yards during their 21.5 hours on the lunar surface. On the other hand, with the first use of the LRV on Apollo 15, a distance of 17.3 miles was traversed and by Apollo 17 this was further increased to 22.3 miles. At one point astronauts were able to work 4.7 miles radial distance away from the LM through the use of the LRV. All told, an area similar to that of Manhattan Island was explored. This was a far cry from the area of one or two football fields, which represented the limits prior to the LRV. Also, it might be remembered that a combination of high metabolic rates and a lack of navigation aids caused astronauts Alan Shephard and Ed Mitchell on Apollo 14 to fall somewhat short of an important scientific objective. In the interest of safety, the flight director of that mission instructed the astronauts to abandon their attempt to reach the lip of Cone Crater when some difficulty was encountered in locating it. The use of an LRV on that mission would have easily solved their problem since it was designed to transport a relatively fatigue-free astronaut to a selected location through the use of an on-board navigation system. Table 1 compares the LRV performance of the final three Apollo missions with that of Apollo 14, which had no LRV but did have a lunar cart that was pulled by the astronauts and contained their tools and sample collection containers. The use of LRVs on each of the last three Apollo missions enabled the astronauts to cover significantly larger areas, accomplish more scientific physical work, and accumulate much more information about the Moon than what had been previously accumulated in the combined rock samples from the prior three missions that had landed on the Moon (Apollo 11, 12, and 14).

TABLE 1. Lunar Roving Vehicle performance comparison.

	Apollo 14	Apollo 15	Apollo 16	Apollo 17
Driving time (hr:min)	N/A	3:02	3:26	4:26
Surface distance traversed (miles)	3.3 (estimated)	17.3	16.6	22.3
EVA duration (hr:min)	9:23	18:33	21:00	21:30
Average speed (mph)	N/A	5.7	4.8	5.0
Max range from LEM (miles)	Unknown	3.1	2.8	4.7 EVA #2
Longest EVA traverse (miles)	1.5 (estimated)	7.75	7.2	12.5 EVA #2
Rock samples returned (lb)	94	170	213	249

GENERAL REQUIREMENTS

The LRV became affectionately known as a "dune buggy," a "moon buggy," the "moon car," etc. It was compared to a golf cart and a small car. The fact is that none of these characterizations was accurate. Although deceptively simply in appearance, the LRV in reality was a highly specialized and complex sophisticated vehicle more aptly described by using the terminology "manned spacecraft on wheels."

The vehicle was designed to be operated in the harsh vacuum of space and with temperature extremes on the lunar surface of ±250°F. Because of anticipated physiological problems with the astronauts' depth perception on the Moon, landing on the Moon at low sun angles was considered a necessary constraint in mission planning. This consideration, therefore, meant that the LRV needed to be designed with a capability to operate in the deep shadows of the mountain ranges for substantial periods of time when temperatures could still be at -200°F to -250°F during the lunar morning. Although intentional use of LRV operation in the shadows was not planned in the mission time line, given all the unknowns of the lunar environment, it did not seem appropriate to constrain the LRV design to only the warm, sunlit portions of the Moon. Thus, even if low weight considerations would not have eliminated the use of traditional rubber tires, the temperature and vacuum constraints did. Figure 1 shows LRV #1 on the lunar surface.

The LRV had to be designed for maximum static and dynamic stability while simultaneously minimizing weight and volume. The stability and weight design considerations were constrained by the requirement that the LRV be capable of carrying two astronauts, tools, science equipment, cameras, television and audio transmission equipment, as well as the weight of the collected rock and soil samples. All this added up to approximately 1100 lbm, which represented considerably more than twice the empty weight of the LRV itself. (By comparison, the average automobile can only safely carry about half its own weight.) In addition, the vehicle had to remain statically stable on slopes of up to 45°.

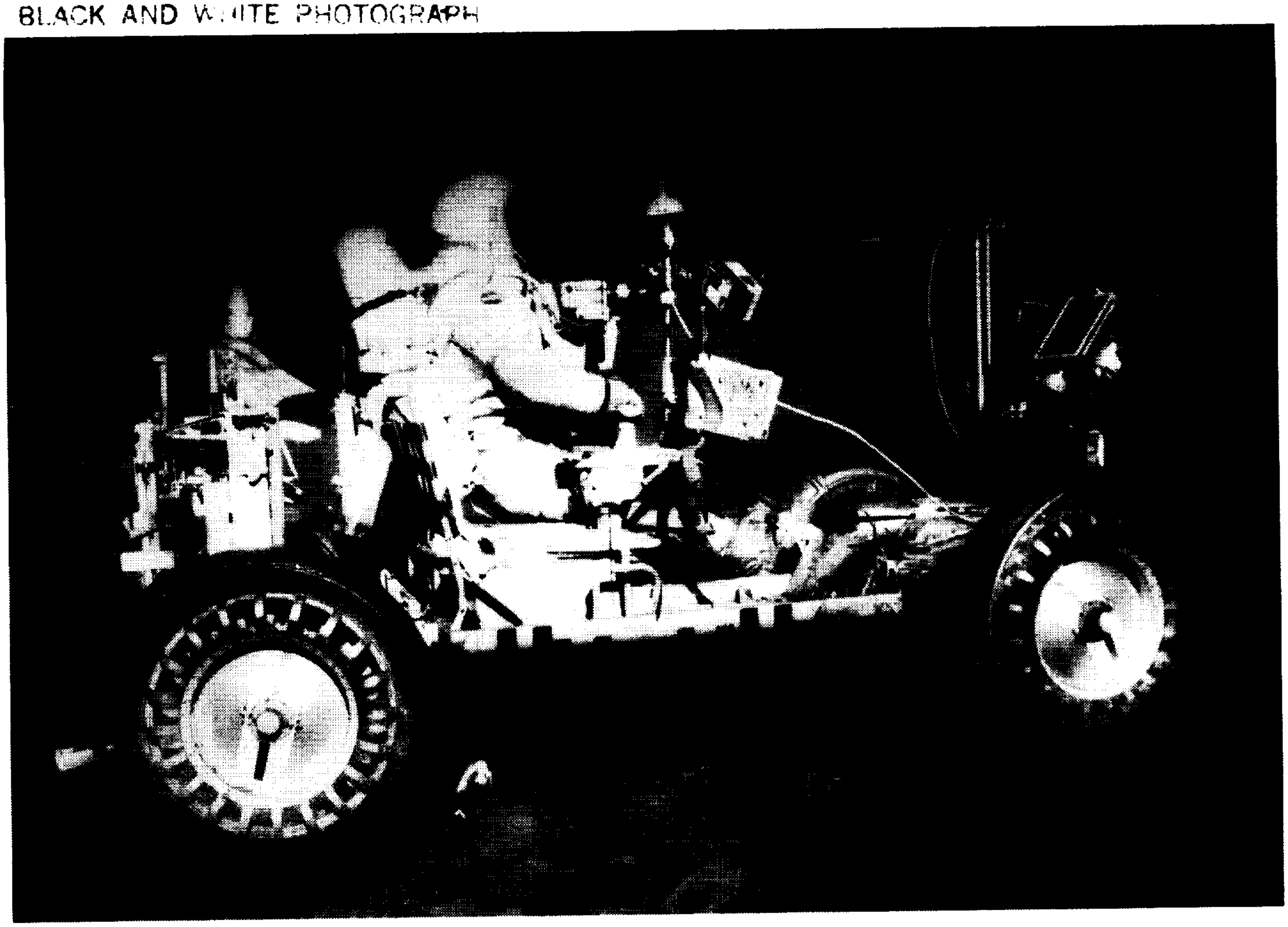


Fig. 1. Lunar Roving Vehicle #1 on the lunar surface during Apollo 15 mission.

Other major design drivers included the requirements that the vehicle be capable of carrying two astronauts in their spacesuits and be operated by either the left- or right-seated astronaut. Because of the extremely limited motions an astronaut had in a pressurized spacesuit, a conventional steering wheel was ruled out in favor of a T-shaped hand controller positioned in front of and between the astronauts. The small limited storage volume of 35 ft^3 available to carry the LRV to the Moon (stowed in a quadrant of the LM descent stage) presented a major design challenge. The solution to the dilemma of the small storage volume available vs. the desire to have a very wide base vehicle for stability purposes resulted in a "folded package" concept for the vehicle (Fig. 2). The final result was like unfolding a vehicle the size of a minicompact car to approximately the dimensions of a full size automobile.

The reliability factors also were a strong design driver. Reliability was attained through a combination of simplicity of design and operations and through redundancy. The redundancy aspect was expressed as a requirement that "no single point failure shall abort the mission and no second failure endanger the crew." This requirement resulted in two independent steering systems (front and rear), two independent battery systems (each

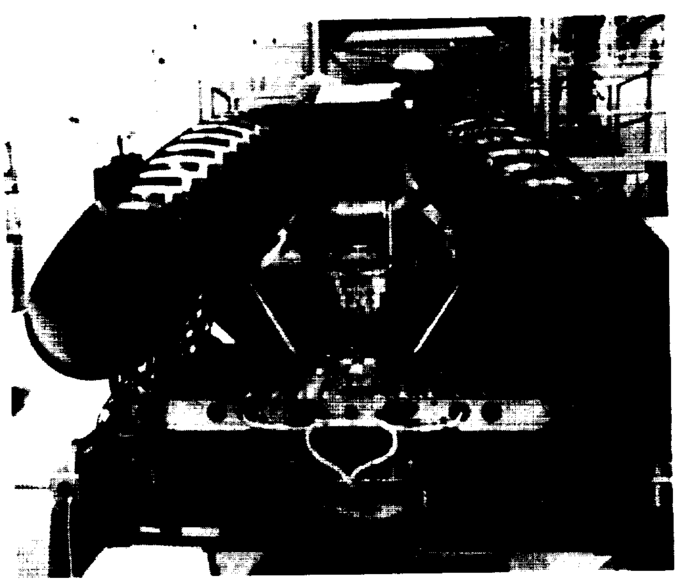


Fig. 2. Lunar Roving Vehicle folded prior to installation in LM.

with sufficient energy to power the vehicle), dual hand controller potentiometers, etc. Circuit and logic protection techniques were also incorporated into the design. These techniques were circuit breakers, velocity limits on changing motor rotation direction, and power interrupt during braking and hand controller return to neutral for steering command. The capability for switching any of the steering or traction drive systems to either, or both, batteries was provided along with independent drive motors for each wheel.

Yet another major design requisite was the consideration that the lunar dust could be a troublesome factor. Remember, very little technical data on the soil characteristics of the Moon were known during the entire development period of the LRV. Attention to the potential dust hazard resulted in designing fenders to prevent the depositing of a "rooster tail" of dust on the vehicle and crew. All moving parts had to be protected against dust, including hermetically sealing the wheel drive motors and traction drive assemblies. Even the slighest coating of dust on thermally radiating surfaces would materially degrade their thermal performance. Thus, during all operations of the LRV, dust covers had to be provided over the radiating surfaces, necessitating storage of the heat until completion of the extravehicular activity (EVA). When the vehicle was parked and the astronauts prepared for their sleep period in the LM, the radiating surfaces of the LRV could then be uncovered and heat rejected to space.

One last major design essential that further confirms the case for the LRV being a "spacecraft on wheels" had to do with the necessity of having a navigation system on board. If EVAs that took the astronauts well out of line of slight of the LM were indeed to be carried out, it would be necessary for the astronauts to know not only where they were at any given moment, but also their most direct route back to the safety of the LM in case of an emergency. Following their tire tracks back to the LM would, of course, have been possible, but would undoubtedly not have been the fastest way to return.

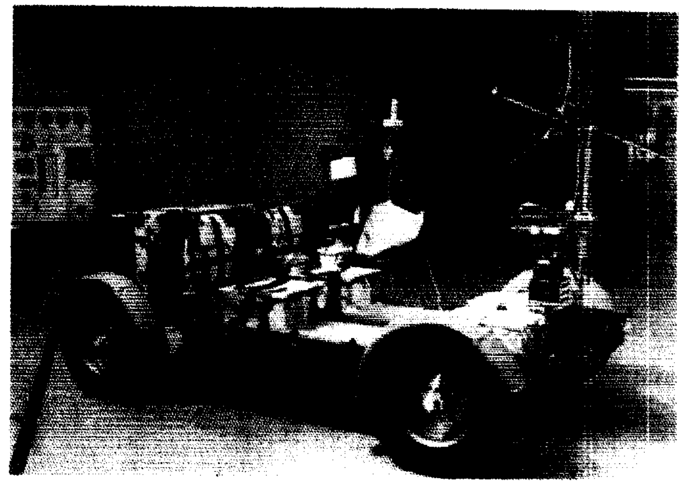


Fig. 3. Lunar Roving Vehicle #1 prior to delivery to KSC for installation on Apollo 15.

SYSTEMS DESCRIPTION

Figure 3 is a photograph of the flight vehicle LRV #1 prior to final acceptance and shipment to KSC for installation into Apollo 15's LM. It consisted of several major subsystems (Fig. 4) that will be discussed. They are the mobility subsystem, the crew station subsystem, the navigation subsystem, the thermal control subsystem, the electrical power subsystem, and the space support equipment or deployment subsystem.

Mobility Subsystem

The mobility subsystem consisted of a three-piece aluminum chassis, four wheels with wire tread tires and independent traction drive assemblies mounted in each hub, a suspension system, a front and rear steering system, and a hand controller with associated drive control electronics system (DCE). With the exception of the chassis subsystem, the rest of these subsystems were designed, developed, and delivered by the General Motors Delco Electronics Division in Santa Barbara, California, under subcontract to the Boeing Company, who was the prime contractor.

Chassis. The chassis (Fig. 5) provided by the Boeing Company consisted of three separate sections: the forward, center, and aft portions. The forward portion supported the LRV batteries, drive control electronics, and navigation electronics and contained mechanical provisions for mounting a power package and antenna for television transmission. The center chassis provided the support for the two astronauts and their fold-down seats, foot rests, the hand controller, the control and display console, and the omnidirectional antenna for voice communication. The aft chassis was used essentially as a platform with mechanical tie-down points for the astronaut tools and scientific equipment, including storage of the lunar material to be collected. (The power package and antenna on the forward chassis, the voice antenna on the center chassis, and scientific equipment and tools on the aft chassis were equipment that was delivered by the Johnson Space Center and installed on the vehicle by the astronauts after the LRV was deployed on the lunar surface.)

All three sections of the chassis were constructed of welded aluminum joined together by hinges. Torsion springs were installed at the forward hinges and were used to assist in unfolding the LRV during deployment on the lunar surface. In a similar manner, torsion bars were used at the aft chassis hinge and served a similar purpose as the torsion springs.

Because minimizing weight was so critical to the design, very careful machining was accomplished on the rectangular tube sections as well as on the chassis fittings in order to remove every unneeded pound of weight. Load testing of the chassis was very critical to confirm the strength of the design, since the analytical techniques alone of these complicated shapes would have necessitated excessive conservatism and, thus, excessive weight.

The floor of the center chasis was made of 2024 beaded aluminum and was capable of supporting the full weight of both astronauts, each wearing a portable life support system in the lunar gravity environment. Here again, with the minimum weight factor being so critical, the LRV overall structure could not have supported the weight of the astronauts in the Earth gravity environment without structural failure. For astronaut training purposes, a special 1-*g* trainer had to be designed and built as part of this program (Fig. 6).

Wheel design. The diameter of the wheel depicted in Fig. 7 was approximately 32 in; it was 9 in wide, and weighed a mere 12 lbm. It was constructed using a spun aluminum hub attached to a traction drive assembly at the inner core and a titanium

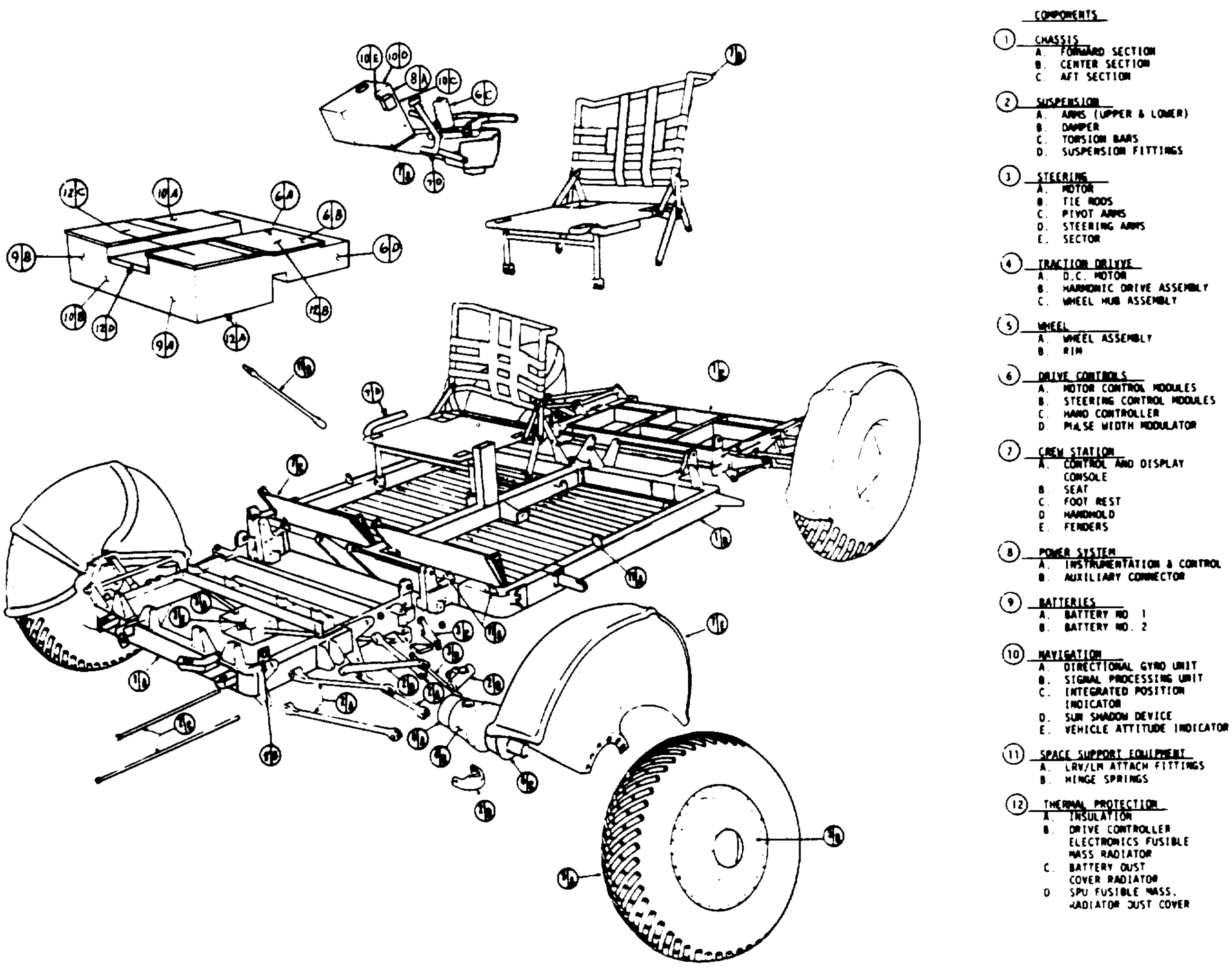


Fig. 4. Lunar Roving Vehicle components.

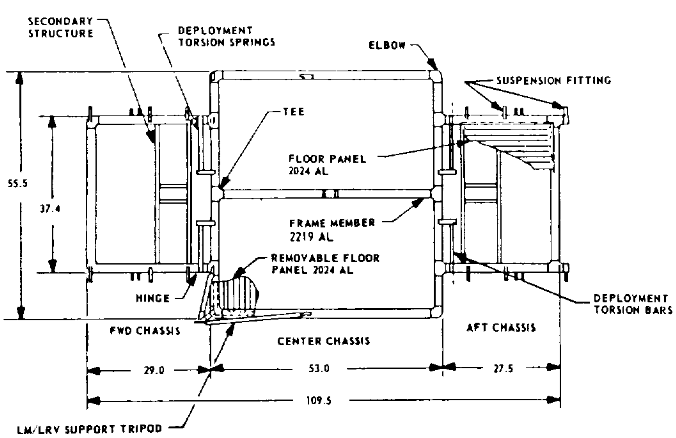


Fig. 5. Lunar Roving Vehicle chassis.

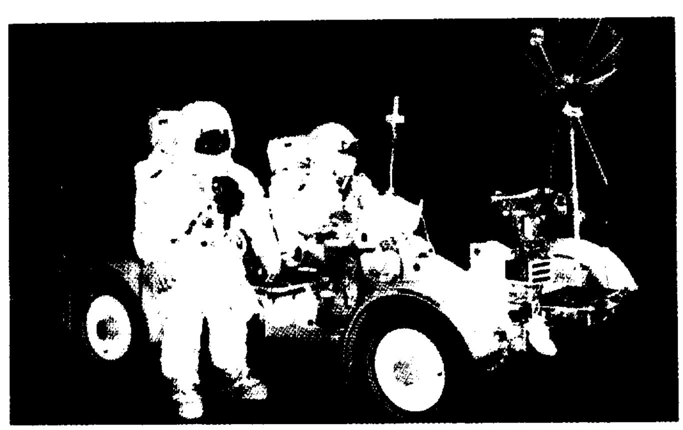


Fig. 6. Earth gravity (1 *g*) LRV astronaut training vehicle.

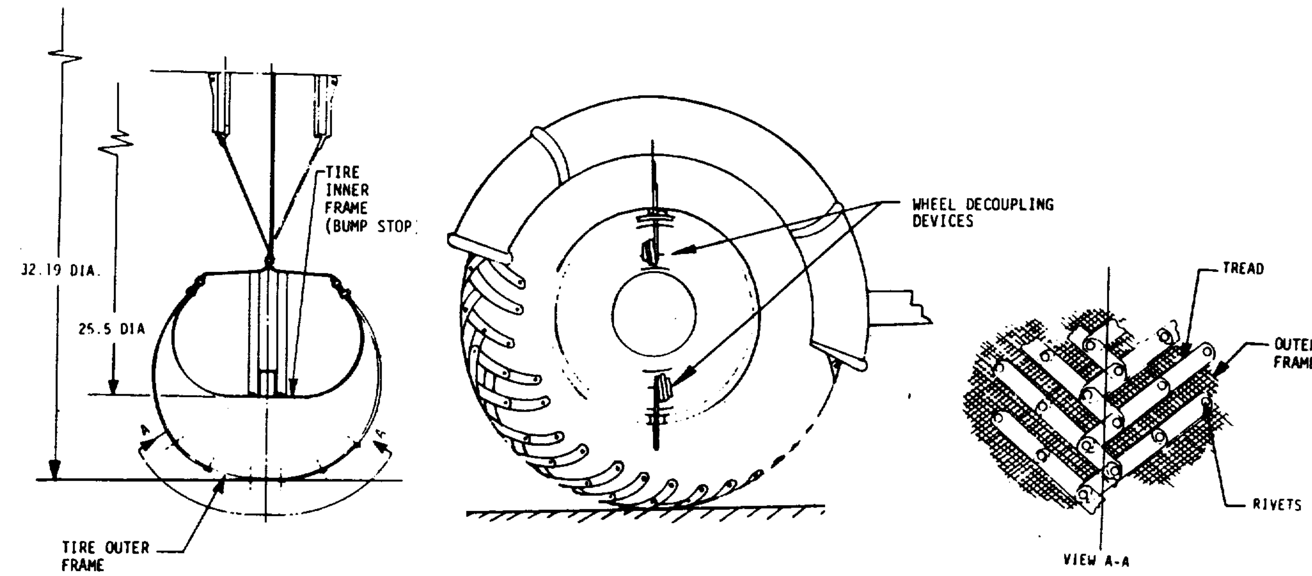


Fig. 7. Lunar Roving Vehicle wheel design.

"bump stop" inside a woven mesh of zinc-coated steel wire (0.033-in diameter) to which a tread made of titanium was riveted in a chevron pattern. Testing with simulated lunar soil at the Government's Waterways Experiment Station at Vicksburg, Mississippi, showed that a chevron pattern that covered 50% of the contact area was optimum and would provide sufficient traction to climb slopes of 20° to 25° without detrimental wheel slip. Endurance testing showed that at vehicle speeds of up to 14 km/hr, rocks with heights as great as 12 in could be struck without wheel or suspension system failure.

Traction drive. The traction drive unit (Fig. 8) attached at the center of the wheel hub consisted of a 1/4 hp series-wound (36 V) dc brush-type drive motor assembly connected directly to a "harmonic drive" assembly with an equivalent of 80:1 gear reduction. The motor and harmonic drive was a totally welded unit, hermetically sealed, and pressurized with nitrogen at 7.5 lb/in^2. Thus, the welded pressurized unit not only provided protection from the lunar dust, but also aided in transferring heat to the hub where it could radiate into space.

The harmonic drive seen in Fig. 9 utilized a unique, yet simple, principle. It converted high speed-low torque to low speed-high torque. The output of the traction drive motor is connected to a wave generator that caused a continuous wave form to be transferred to a flexible spline. A significant gear reduction ratio was developed by having two less teeth on the flexible spline than on the circular spline, thus avoiding the necessity for providing a much heavier conventional gear reduction mechanism. Incorporated into each traction drive assembly was a magnetic reed switch that activated nine times during a single wheel rotation. The pulses generated in this manner were subsequently used in the odometer, speed, and navigation calculations. It might be mentioned here that the use of the harmonic drive principle did not evolve out of the space program, but rather from the shoe machinery business in this country.

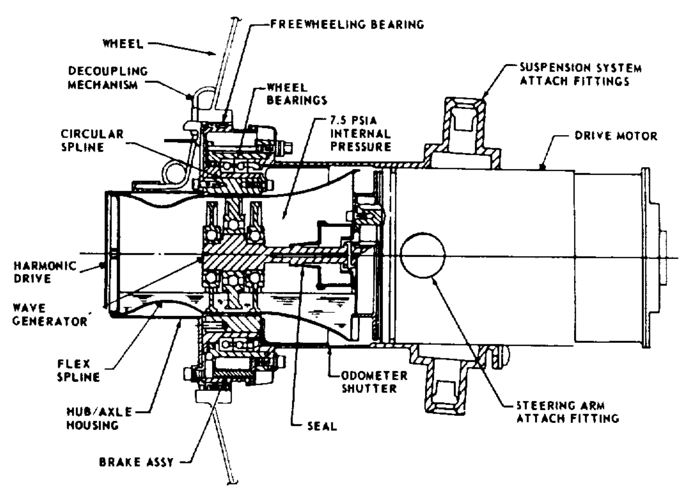


Fig. 8. Traction drive assembly.

To prevent disabling the LRV because of a traction drive assembly failure, design provision was made to enable manual decoupling of the wheel from the traction drive and brake. This was accomplished by pulling the decoupling ring seen in Figs. 7 and 8 with a part from the two tripods left over from the LRV deployment operation. (A portion of one of these tripods doubled as a special tool to accomplish this decoupling.) Once decoupled from the traction drive assembly, the wheel could be left to "free wheel," around the traction drive assembly. The remaining three engaged traction drive assemblies provided the drive power to the operational wheels. Analytically, it was shown that the LRV could be driven in an emergency mode with only one of the four traction drive assemblies engaged (three wheels "free wheeling").

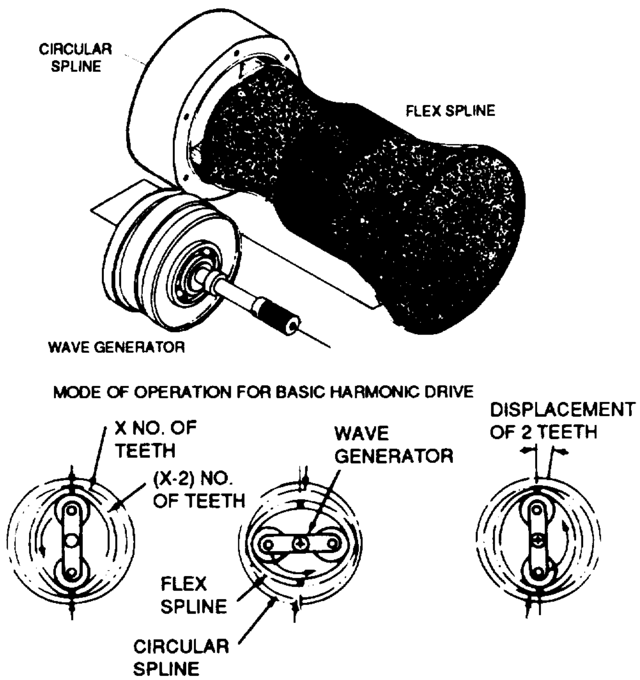


Fig. 9. Harmonic drive.

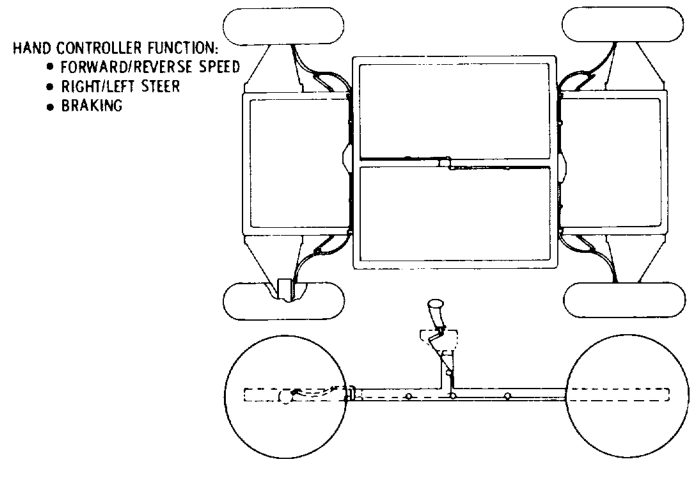


Fig. 10. Hand controller/brake cable system.

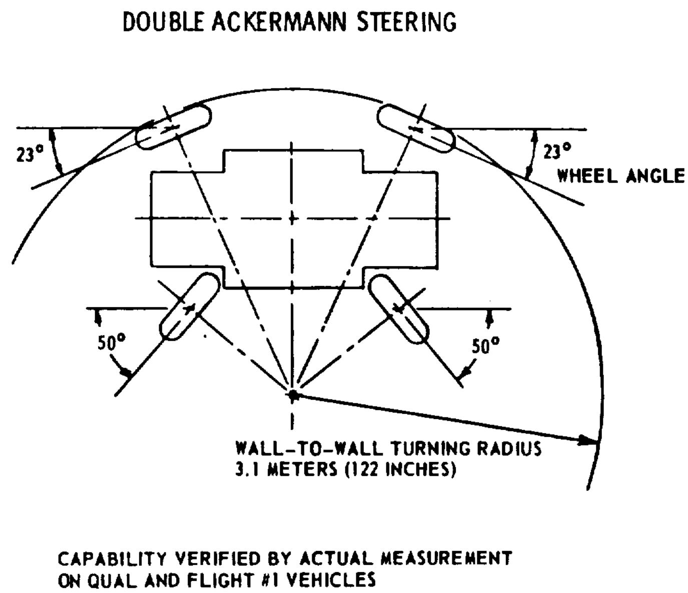


Fig. 11. Steering assembly.

Braking was accomplished via a cable connecting the hand controller and the mechanical shoe and drum system on each of the four wheels (Fig. 10). In addition to normal drive braking, the system was also set by the hand controller as a parking brake. In the event of a brake lock-up, possible sag as the result of excessive temperature from extra lengthy parking under adverse solar heat load, or excessive use of brakes during driving, the brakes could be released from the park position by a pull-ring mounted below the hand controller.

Steering. In an effort to reduce total power needs, increase maneuverability, and provide redundancy in all critical systems, the front and rear wheels were designed with independent, modified Ackerman steering subsystems. Each subsystem consisted of a small 0.1-hp, series-wound, split-field, 500-rpm motor driving through a 257:1 gear reduction into a segment gear that connected with each traction drive motor by steering arms and a tie rod. This independent front and rear steering system permitted a vehicle turning radius of 122 in "wall-to-wall," enabling the LRV to turn within its own length (Fig. 11). A steering vane attached between the chassis and the steering arms allowed the extreme steering angles required for the short turning radius. Steering response was rapid, requiring only 5.5 sec from lock to lock, with reversals accomplished by switching field windings through the hand controller subsystem. The beauty of the modified double Ackerman system was that it allowed the rear wheels to always track the front wheels, even in the sharpest of turns, thus providing maximum maneuverability while minimizing the power required for locomotion.

In the event of a steering malfunction, or in the event that the steering would have been overly sensitive, the astronauts had the capability to electrically turn off either the front or rear steering. In addition, the astronauts could mechanically disengage and lock either front or rear steering by pulling a ring on the side of the chassis and mechanically locking the steering system in the center position. If it were necessary to reengage following the disengagement of either steering subsystem, this could have been accomplished through the use of a special tool carried on the LRV. All this redundancy seemed like a large price to pay; however, as the reader may recall, the entire first EVA on Apollo 15 had to be conducted with rear steering only. Although the steering malfunction was resolved during the rest period between EVAs, a significant impact to the mission would have resulted if the LRV had to be dropped from EVA #1 due to lack of steering capability.

Suspension. The remaining suspension elements completing the mobility system consisted of a dual A-frame attached from the hub of each wheel to the chassis via two torsion bars and a shock absorber (Figs. 12 and 13). The torsion bars of different sizes provided ride comfort by reacting the dynamic driving loads into the chassis structure. More than 80% of the load was reacted by the longer of the two torsion bars. The smaller bar served

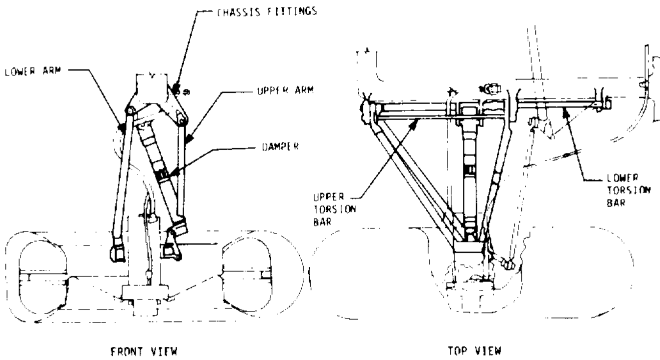


Fig. 12. Lunar Roving Vehicle suspension system.

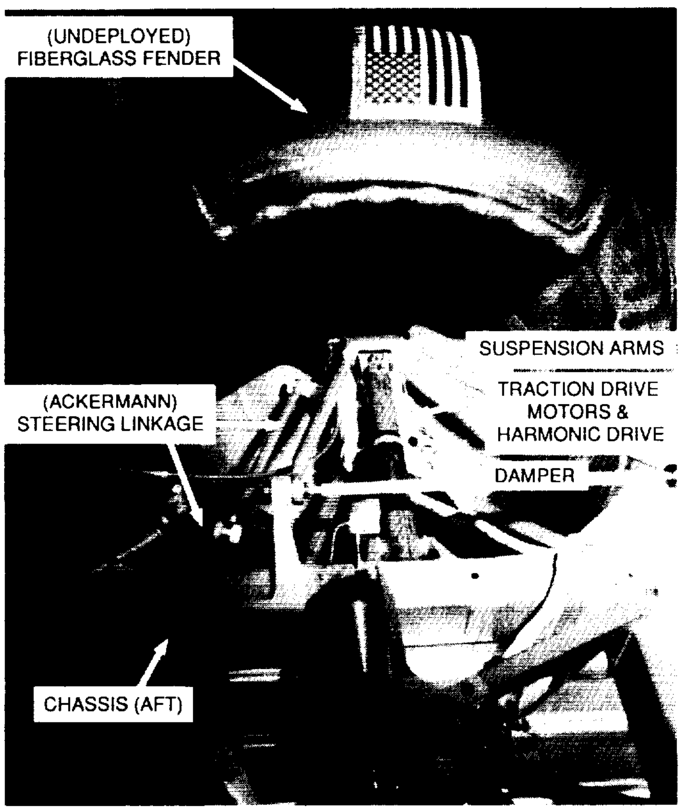


Fig. 13. Lunar Roving Vehicle suspension system.

primarily as a deployment aid during the initial unfolding operations and was the only one of the two bars loaded while in the stowed position. This approach limited any "creep" tendency of the bar material and/or assembly to the secondary (smaller) torsion bar, thus leaving the primary bar unloaded until the vehicle was ready for driving. Each wheel also had a linear piston damper or shock absorber that was somewhat telescoped during storage and then extended upon deployment. The linear piston damper was selected due to its design simplicity, light weight, and efficient loading of the suspension structure.

Drive control electronics (DCE). The DCE package was located on the forward chassis of the vehicle and was the electronic heart of the mobility system. This package accepted forward and reverse speed control signals as well as left or right steering commands through a process called "pulse width modulation" (Figs. 14 and 15). It featured redundant circuitry and dual power supplies. The DCE provided signal processing logic to pulse width modulators that in turn furnished energy to both the traction drive and steering motors. The square-wave pulse, providing power to the traction drive, varied in width, thereby varying applied power as a function of the speed command from the hand controller potentiometers. The traction drive motors pulse rate was 1500 Hz, whereas that of the steering motors was 10,000 Hz. Heat generation from the DCE had to be stored until after the completion of an EVA in order to prevent heat radiation surfaces from being impaired in their function by dust accumulations. More will be said about this in the discussion of the thermal control system.

Crew Station Subsystem

The LRV crew station subsystem (Fig. 16) consisted of two foldable seats, two seat belts, two foldable foot rests, a hand controller, one arm rest behind the hand controller, inboard and outboard hand holds, two toe holds, and the control and display console. In addition, fenders for the wheels and the floor panels of the center chassis were considered as part of the crew station. They were required primarily because the LRV was manned.

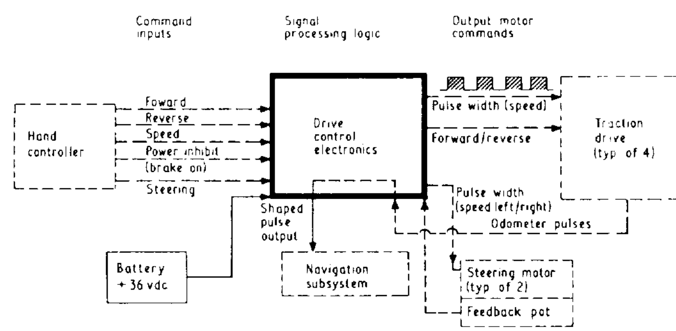


Fig. 14. Drive control electronics operation schematic.

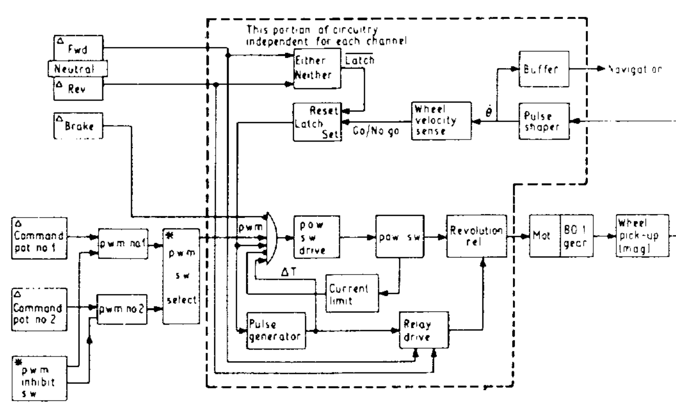


Fig. 15. Drive control circuit block diagram.

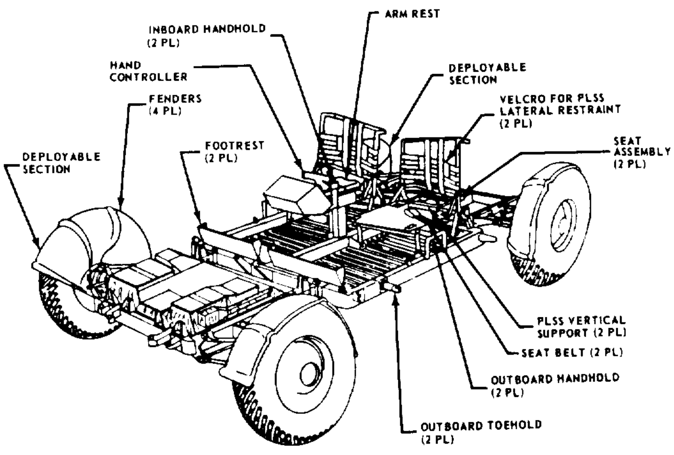
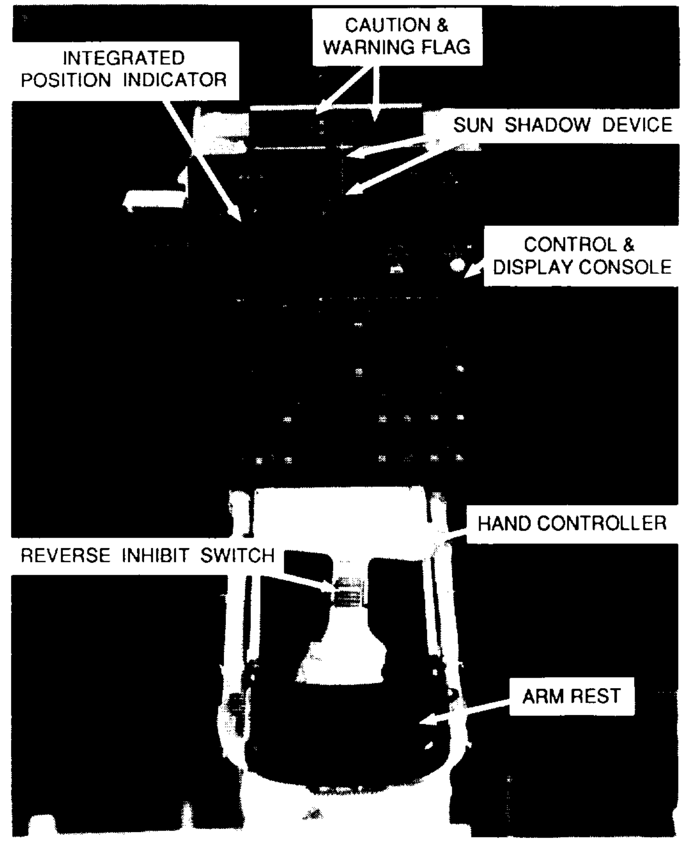


Fig. 16. Crew station subsystem components.



The LRV's seats and foot rests were folded flat onto the chassis during preflight installation and were deployed by the astronauts upon reaching the lunar surface. The seats were of tubular aluminum construction spanned by nylon strips and, together with the back, supported and restrained the astronauts' portable life-support system (PLSS) from sideways and vertical motion while driving. Cutouts were provided in the seat bottoms to enable access to the PLSS flow control valves at all times. Seat belts were made of nylon webbing with an adjustable web section and a metal hood that snapped over the outboard hand hold for quick ingress and egress activity.

A toe hold on each side of the vehicle was used to aid the astronauts in getting in and out of the vehicle. Toe holds were incorporated as the result of early KC-135 flights simulating the $1/6$-*g* environment of the Moon. These tests showed rather conclusively that the astronauts required the assistance of a toe hold in order to be able to quickly assume the seated position on the vehicle. The toe hold then could serve as a removable tool in order to activate the wheel decoupling mechanism should circumstances have arisen that required such action. The toe holds themselves were assembled on the lunar surface by dismantling two tripods that connected the LRV to the LM while in the stowed position. These were then inserted into receptacles located on each side of the chassis.

Hand controller. All functions relating to steering, speed control, braking, etc. were handled by a T-shaped hand controller located between the two astronauts and just aft of the control and display console (Fig. 17). Tilting the controller forward of the neutral position proportionally increased forward speed. Reverse power was applied when the controller was tilted backwards past the neutral position after a reverse inhibit switch on the side of the hand controller was activated by the astronaut. With the reverse inhibit switch in the down position, the controller could only be pivoted forward for forward driving. With the switch in the upward position, the LRV could be operated in reverse. Braking was initiated when the controller was pulled backward. At approximately 3 in of aft travel, a spring-loaded catch engaged the handle to lock in the "park" position. Forward and reverse power was cut off when the braking action began. A simple tilting of the hand controller to the left released the parking brake.

Moving the controller left or right caused the vehicle to steer left or right, respectively. As the controller was spring-loaded, it would return to the neutral steering position when released. The hand controller moved a series of redundant potentiometers located in its base, which were used to apply command bias signals to the DCE package for all drive and steering commands. The exception to this electronic drive control was the braking function, which applied tension to the brake control cables mechanically, as previously discussed.

Control and display (C&D) console. The C&D console consisted of an upper portion containing navigation system instruments and a lower portion containing controls for switching and monitoring electrical loads. To enable easy reading of the instruments and switches in shadows, the panel markings were irradiated with promethium 147. Located on the upper left side of the console was an attitude indicator (AI) that provided pitch and roll information within a range of $\pm 25°$. In the position shown in Fig. 18, upslope (U) or downslope (D) attitude could be read. Roll angles were obtained by rotating this indicator forward. This action exposed a "roll" scale to the left crewman. This indication was read by the crew and reported to Mission Control Center (MCC) during navigation update where, with ephemeris data, vehicle heading could be determined. The vehicle attitude data were used by MCC to correct the sun shadow device readings if the LRV was not level. This sun shadow device, located in the upper portion of the console, helped determine the LRV heading with respect to the sun and was compared with the directional

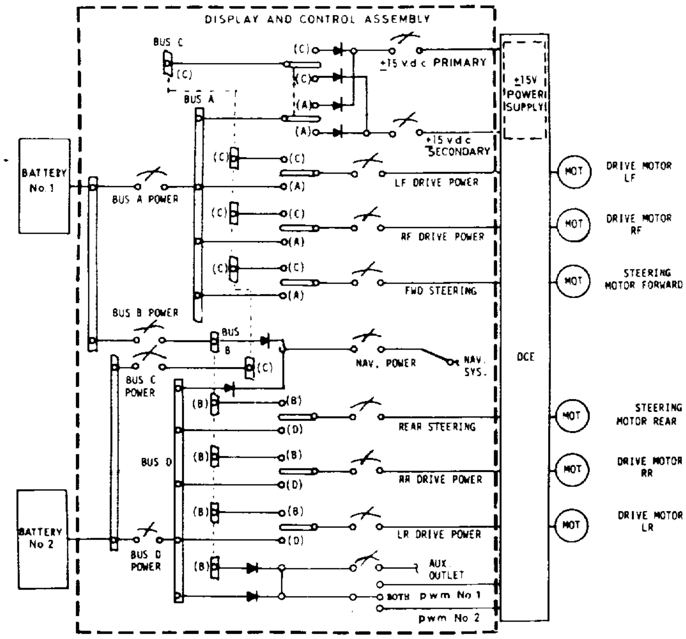


Fig. 18. Electrical power distribution diagram.

gyro as check against gyro drift. When lifted into position, the sun shadow device would cast a shadow on a graduated scale, the value of which was radioed to MCC during navigation updates.

Also located in the upper portion of the C&D console was a heading indicator (HI) that displayed LRV heading with respect to lunar north, a bearing indicator (BI) that always showed a bearing directly back to the LM, a range indicator (RI) that always showed distance directly back to the LM, and a distance indicator (DI) that showed distance traveled in increments of 0.1 km. This information was obtained from the navigation signal processing unit (SPU) located on the forward chassis that in turn received its signal from the third-fastest traction drive odometer. The third fastest odometer value was selected to minimize errors caused by wheel slippage and/or to insure against using the output impulses from a wheel that was decoupled and "free wheeling."

The gryro torquing switch was used to adjust the HI during navigation updates. The NAV power circuit breaker was used to route power from the main buses to the navigation susbsystem. The power distribution was designed in such a way as to enable power for the navigation system to be obtained from both batteries simultaneously. This would prevent a critical failure in the event that one battery failed (see electrical power distribution diagram, Fig. 18).

A speed indicator (SI) depicted LRV speed from 0 to 20 km/hr and utilized pulses only from the right rear wheel. The system reset switch was used to reset the bearing, distance, and range digital displays to zero. Lastly, sitting on top of the console was a caution and warning flag used to give the crewmen a visual warning if either battery or if any traction drive motor were overheating. The spring-loaded flag was held down by an electromagnet whose circuit was designed to open in the event of an overheat problem (exceeding 125°F on either battery or 400°F on any drive motor). Should this have occurred, the flag would have immediately popped into full view of the astronauts.

The lower portion of the console contained a power section, a power/temperature monitor section, a steering section, a drive section, and a drive enable section. The power section consisted of circuit breakers that connected the batteries to the main power buses, the auxiliary outlet circuit breaker for power to the communications relay unit, and the circuit breakers and control switch for the ±15 Vdc power to the pulse-width modulators. With four main power buses, any drive motor, steering motor, etc. could be connected to either battery, thus providing full redundancy.

The power/temperature monitor section provided the status of the vehicle's electrical system and temperature of batteries and motors. Battery voltage and current flow from either battery could be displayed when the crewman used the appropriate volts-amps switch position. Similarly, the position of the drive motor temperature select switch determined whether the rear or front wheel motors were to be displayed. In addition, a battery amp-hour integrator meter was provided, which displayed the remaining battery capacity (set at 121 amp-hours prior to the first LRV use on the EVA).

The steering section contained a switch and a circuit breaker for each of the two steering motors. Similarly, the drive and power section had circuit breakers and switches for each of the four drive motors. The remaining section was for drive enable. This section contained a switch for each drive motor that permitted the astronaut to select either pulse width modulator (PWM 1 or 2). As previously discussed, the PWMs provided speed control signals for each motor. The switch just above this section enabled the astronaut to select PWM 1, 2, or both. Here again, redundancy was the uppermost consideration throughout the design. Any motor could be supplied by any PWM, or all motors could be driven from one PWM.

Navigation Subsystem

The navigation system consisted of three major components. They were the directional gyro (DG), odometers on each traction drive assembly that provided distance and speed information, and a small solid state computer. The navigation subsystem was based on the principle that when starting a sortie from a known point, entering speed, direction, and distance traveled information into an onboard computer, and then computing vehicle position from these data by solving a relatively simple trigonometric problem, would provide bearing and distance back to the LM (Fig. 19). Inputs to the navigation subsystem were changes in the LRV direction with respect to lunar north (obtained from the DG) and odometer pulses that were obtained from the wheel rotation of the third fastest wheel. For each increment of distance measured by the odometer circuitry, the signal processing unit (SPU) would calculate the east-west and north-south distances traveled based on vehicle heading data obtained from the gyro. These distances were summed with related distances already in the registers, and range and bearing to the LM automatically calculated and then displayed on the C&D console (see prior discussion).

The overall accuracy requirements of the navigation system were that the system needed to be capable of determining the bearing to the LM relative to lunar north within ±6° at a radius of 5 km from the LM. In addition, the distance from the LR to the LM had to be within ±600 m, again at a radius of 5 km. The system had to be capable of displaying the distance traveled at

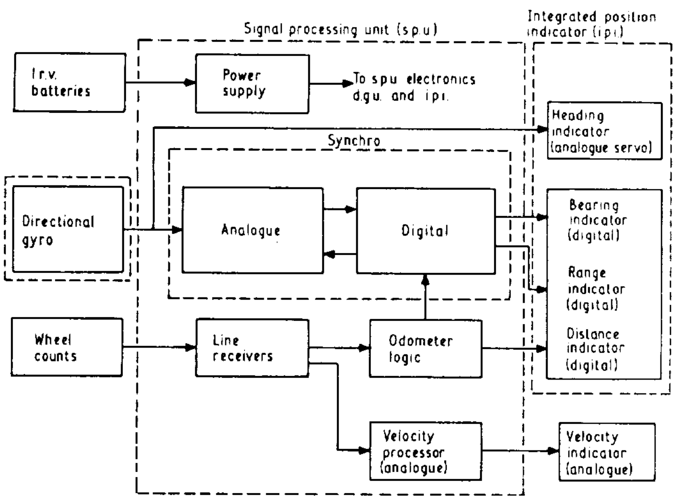


Fig. 19. Navigation system block diagram.

any point in the traverse to an accuracy of ±2%. (These requirements were met on the lunar surface with considerable margin.)

Reverse operation of the vehicle produced some error as the odometer logic could not distinguish forward or reverse wheel rotation. Thus, odometer pulses generated while operating the vehicle in reverse were seen by the SPU as forward motion. Although this would undoubtedly introduce some error, it was determined that the error would be so minor that it was not worth the extra cost, weight, and complexity to design into the SPU a network that would allow such correction.

Thermal Control Subsystem

The LRV made use of a passive and semipassive system of thermal control (Fig. 20). The system included special surface finishes, space radiators, multilayer insulation, thermal straps, and fusible mass heat sinks. At liftoff from the Cape, LRV storage volume temperatures were maintained at 70°F ± 5°F. Insulation and reflective coatings were used to control the heat loss of various critical components during boost, Earth orbit, translunar flight, and lunar landing. It was important for the batteries to be maintained between 40°F and 125°F. Other equipment had wider temperature tolerances between -30°F and 185°F.

The basic concept of thermal control on the lunar surface consisted primarily of storing heat during vehicle operation and rejecting heat to deep space by radiation while the vehicle was parked between EVAs. Thus, during operation, heat generated was stored in heat sinks consisting of two LRV batteries and tanks containing wax-like phase change material. At the completion of an EVA, the astronauts would park the vehicle in a specific orientation with respect to the sun in order to achieve the most favorable cool-down attitude and then lift three dust covers from the forward chassis, exposing fused silica second-surface mirrors that were the heat radiating surfaces. The radiators had to be totally covered during LRV operation to prevent dust accumulations, which would effectively destroy the radiation properties of the mirror. When opened by the astronauts, the dust covers were held open by a throw-over locking mechanism. During the astronauts' rest/sleep period between EVAs, the heat stored by the batteries and the tanks containing the phase change material would be rejected to space. This heat rejection would continue until battery temperatures came down to 45°F (±5°F), at which time a bimetallic spring device would disengage the throw-over latch, allowing the covers to be closed automatically.

During LRV operation, the covers provided dust protection to the DCE, the SPU, the DGU, and the LRV batteries. Passive protection was provided by multilayered aluminized mylar and nylon netting insulation blankets with a "beta cloth" (polished glass) outer layer that was necessary to protect against wear and direct solar impingement.

Instruments on the C&D console were mounted on an aluminum plate that was isolated from the rest of the vehicle through the use of fiberglass mounts. The external surfaces of the console were coated with a heat-resistant paint, with the face plate being black anodized for temperature control while reducing reflections that were annoying to the astronauts. Heat generated by each of the traction drive assemblies and the shock absorber (linear dampers) was radiated to space through the hubcap disk and the casing, respectively. The pressurized gas inside each of the traction drive assemblies aided in this process of heat rejection.

Electrical Power Subsystem

This subsystem consisted of two 36-V silver-zinc batteries, a wire distribution system, connectors, circuit breakers, switches, and meters (Fig. 18). Both LRV batteries were designed for minimum weight and consisted of plexiglass monoblock (common cell wall) construction, 23 cells with silver-zinc plates, potassium hydroxide as the electrolyte, and a magnesium case. The batteries were rated at 121 amp-hours each and were normally operated simultaneously with approximately equal loads. As previously discussed, through selective switching at the control and display console, the total or any part of the electrical load could be carried by either battery alone. The batteries were located on the forward chassis and were enclosed by thermal blankets and dust covers. Each battery was protected from

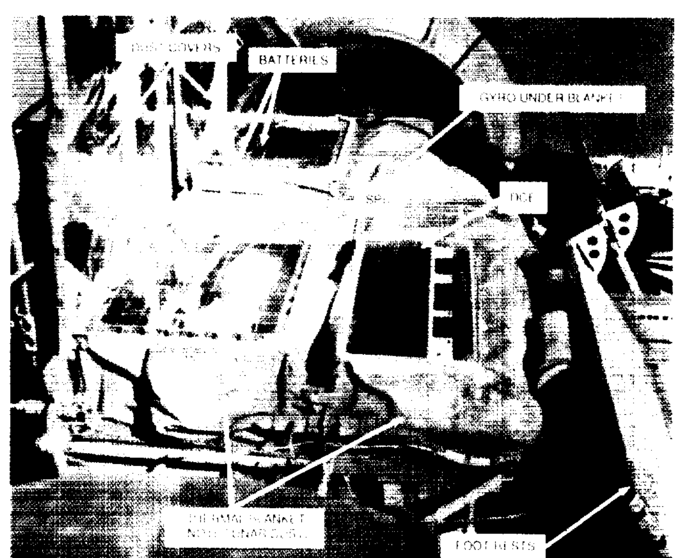


Fig. 20. Portion of thermal control system.

excessive internal pressure by a relief valve and from excessive temperatures by monitoring at the C&D console during operation and radiators exposed between sorties, as previously discussed under the Thermal Control section. Because the batteries were used as heat sinks (battery #1 was connected by thermal straps to the navigation system's SPU and battery #2 to the navigation system's DG), careful monitoring and control of their temperatures was essential.

Stowage and Deployment Subsystem

Because of the stability requirements for a two-man vehicle and the volumetric constraints dictated by the LM and upper-stage fairing, it was necessary that the LRV be transported to the Moon stored in a folded configuration and then deployed after arrival on the lunar surface. Figure 21 shows the LRV in the typical folded position just prior to installation and integration into the LM. In the LM, the folded LRV was supported and secured by space-support equipment that also served to deploy the vehicle once on the Moon.

The space-support and deployment equipment had to be designed with sufficient capability to enable a deployment of the LRV to take place in less than 15 min (worst case) with the LM tilted at any angle up to 14.5° in any direction and with the bottom of the descent stage anywhere from 14 in to 62 in above the lunar surface.

This support and deployment mechanism, shown in Fig. 22, consisted of cables, shock absorbers, pin retraction mechanisms, telescoping tubes, push off rods, and other pieces required to deploy the vehicle. The actual deployment was accomplished by the astronaut pulling on two nylon tapes. While standing on the LM access ladder, the first step by the astronaut was to pull a "D"-handle. This action served to retract three pins holding the LRV to the attach points, thus freeing the LRV for the deployment sequence. A spring-loaded push-off rod, shown in the upper portion of Fig. 22, thus began to move the folded vehicle away from the top of the LM storage bay by some 5 in until it was stopped by two steel deployment cables.

At this point the astronaut descended the LM access ladder, walked around to the LRV's right side, and began to unreel the nylon tape in a hand-over-hand manner, slowly lowering the vehicle to the surface (see sequence in Fig. 23). After approximately 15° of deployment motion, the lower end of the vehicle was rotated onto the two lower points just outside the bay formed by tripods attached to the LRV's center chassis. As the chassis reached approximately 45° in rotation, release pins on the forward and aft chassis were automatically pulled. This action caused the aft wheels to unfold, assisted by torsion bars, until latched and locked. The astronaut continued unwinding the tape until, at approximately 73° of rotation from the LM, the forward chassis and wheels were automatically deployed and locked. At the 73° point in the deployment, a cam released latches on the support arms, which served as the rotation axis allowing the telescoping tubes to extend further, thus holding the LRV away from the LM.

At this point the astronaut pulled the second operating tape located on the left side of the LM quadrant, allowing the forward end of the LRV to be gently lowered to the surface and causing

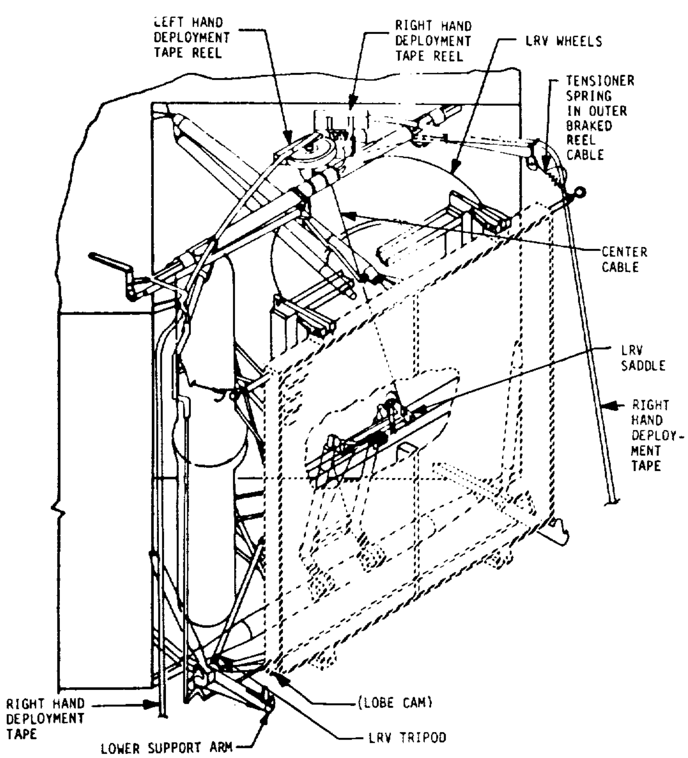


Fig. 21. Lunar module/space-support equipment with LRV installed.

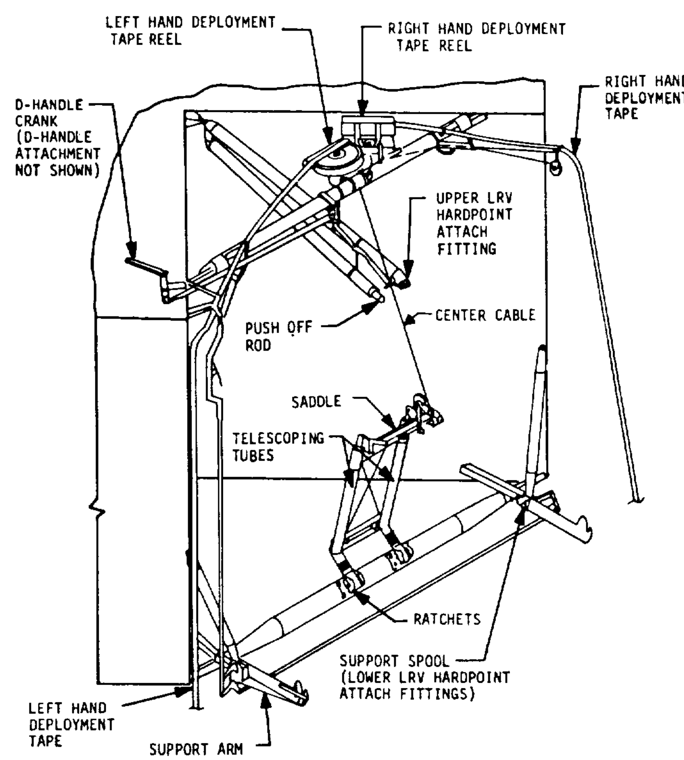


Fig. 22. Space-support equipment.

the telescoping tubes attached between the LRV and the LM to guide the LRV away from the LM. This action was followed by the astronaut pulling a release lanyard at the forward chassis' left side, allowing the telescoping tubes to fall away.

After the LRV was disconnected from the LM and space support and deployment equipment, the astronauts would insert toe holds, erect seats and foot rests, deploy wheel fender extensions, release seat belts, and remove docking pins and latches from several places on the vehicle.

At this point, one astronaut powered up the LRV, confirmed all controls were working properly, and then proceeded to back the vehicle away from the LM and drive it to the side of the LM where the auxiliary equipment was stored. The vehicle was powered down and the auxiliary equipment mounted on the LRV. This included the lunar communications relay unit (LCRU), the ground control television cameras assembly (GCTA), the voice and television antennas, and the aft pallet containing most of the hand tools and science instruments needed for the sorties.

SUMMARY

In summary, there are two salient issues worth re-emphasizing. The first deals with the initial purpose of the paper: to revisit the LRV design and program in some specific detail in order to provide contemporary space exploration planners with an opportunity to become more knowledgable of this "spacecraft on wheels," which operated so successfully on three separate missions to the Moon. Conceivably, by some modifications to this vehicle or by some evolutionary redesign, this vehicle could possibly satisfy requirements for a roving vehicle inferred by the potential new national thrusts in space. It is hoped that this paper might be the catalyst to spark a renaissance for the LRV.

The second point deals with the validity of the terminology "spacecraft on wheels," which was referred to early in the paper. What may have been viewed as a locomotion device truly embodied the sophistication of a spacecraft, as supported by the detail provided in this paper. The astronauts who had the privilege

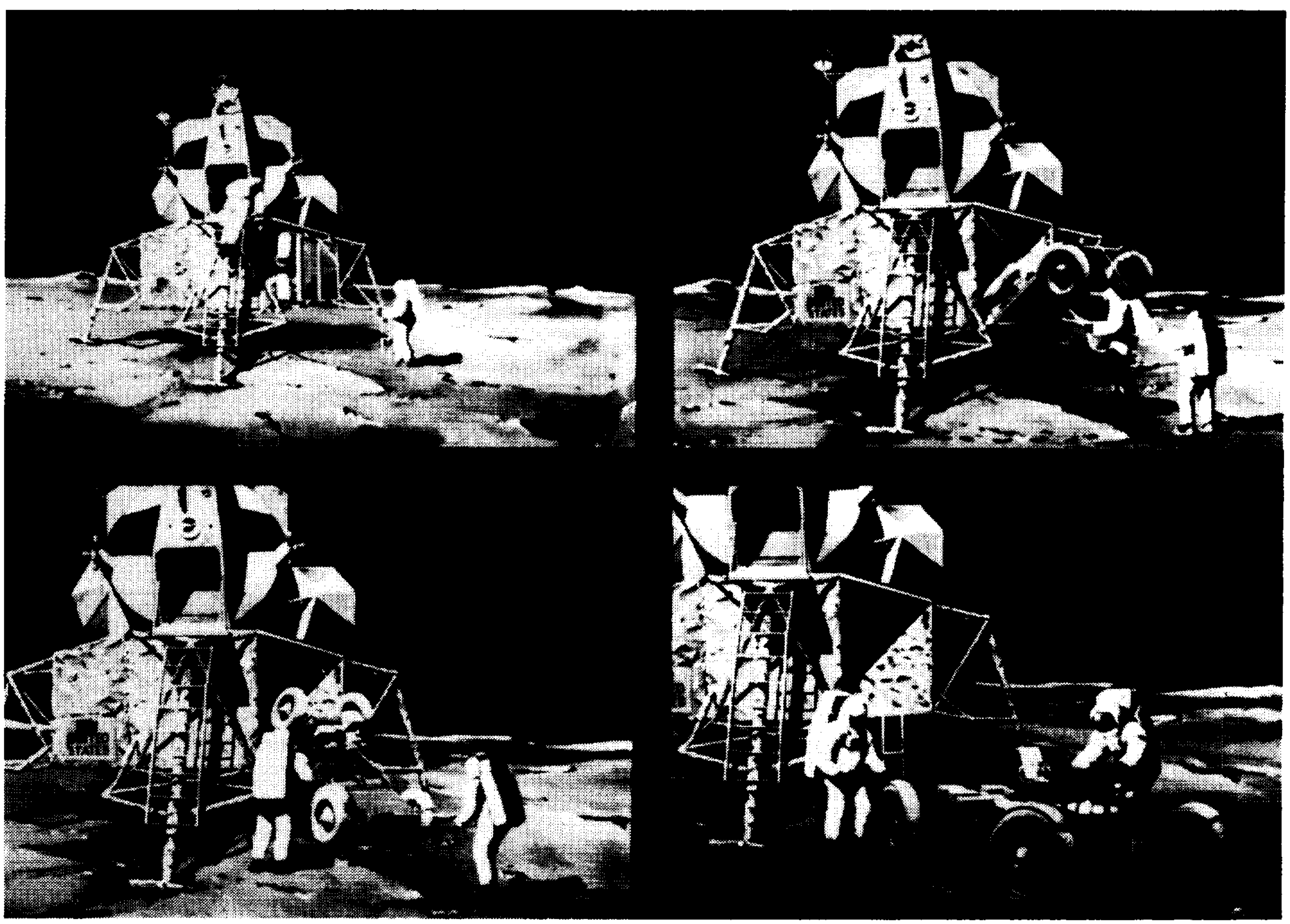


Fig. 23. Deployment sequence.

of driving this machine on the lunar surface [D. Scott, J. Irwin (Fig. 24), C. Duke, J. Young, G. Cernan, and J. Schmitt] all had very positive comments about its handling, performance, reliability, and the sort of machine the LRV was. In fact, the superlatives flowed quite easily in all the mission debriefings. The crew of Apollo 17 (G. Cernan and J. Schmitt), upon their return to Earth, had nothing but praise for the LRV:

> "The Rover performed admirably . . . that vehicle that sits out there at Taurus Littrow—We talked an awful lot about having two good spacecraft, but we told ourselves that we had *three good spacecraft*. That thing couldn't perform better—and we pushed it in many cases to the limit. But let me tell you that vehicle for a long time was just a little bit better than we were because it's a super performing vehicle. If you take a couple more batteries up there, that thing would just keep going . . ." (emphasis added)

Such glowing testimonials from the men who used the LRV offer more compelling arguments for its merits than this paper could hope to do.

Fig. 24. Astronaut Irwin with rover at Apollo 15 landing site.

N93-14009

MOBILE WORK PLATFORM FOR INITIAL LUNAR BASE CONSTRUCTION

James W. Brazell, Brice K. MacLaren, Gary V. McMurray, and Wendell M. Williams

The George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta GA 30332

Described is a system of equipment intended for site preparation and construction of a lunar base. The proximate era of lunar exploration and the initial phase of outpost habitation are addressed. Drilling, leveling, trenching, and cargo handling are within the scope of the system's capabilities. The centerpiece is a three-legged mobile work platform, named SKITTER. Using standard interfaces, the system is modular in nature and analogous to the farmer's tractor and implement set. Conceptually somewhat different from their Earthbound counterparts, the implements are designed to take advantage of the lunar environment as well as the capabilities of the work platform. The proposed system is mechanically simple and weight efficient.

INTRODUCTION

Conceptual design is in progress for a system of equipment to conduct site preparation and construction on the lunar surface. This effort is centered in the Engineering Design Laboratory at the Georgia Institute of Technology in conjunction with the NASA/USRA University Advanced Design Program.

Minimal attention has been previously directed to the phase of lunar surface activity that spans the period between the landing of construction equipment on the Moon and the habitation of a lunar base. Many of the artistic renderings have envisioned familiar types of equipment such as the bulldozer and the backhoe constructing lunar habitats. Engineering analysis shows the impracticality of such terrestrial equipment that has not been uniquely designed for the lunar environment. In particular, such traditional equipment typically depends on its earthly weight for counterbalance as well as reaction to applied forces.

Deliverability to the Moon and the absence of human operators during the unmanned phase of surface preparation places additional constraints on the design and implementation of any construction equipment. The approach for this proposed system uses mechanically reliable, multipurpose vehicles and implements to overcome operational and transportation constraints.

A three-legged walker is proposed as a mobile work platform for most of the activities involved in lunar base site preparation and construction. Using the principle of dynamic stability and taking advantage of the Moon's gravity, it is capable of walking in six preferred directions and rotating about a point. The platform is envisioned to be a lunar version of the farmer's tractor where a variety of implements, such as crane or drill assemblies, are attached. By using the inherent stability of a three-legged structure, along with SKITTER's unique capability for complex motion, the implements can accomplish a variety of complicated operations efficiently.

MOBILE WORK PLATFORM: SKITTER

SKITTER is a comparatively simple device from a mechanical point of view. The central body serves as a housing for supporting hardware and control instrumentation as well as a host for a variety of implements attached via upper and lower body inter faces (Fig. 1). The legs are essentially identical to one another each connecting to the central body by a hinged joint referre to as a hip. A femur link connects the hip and knee joints. Another hinged joint, referred to as the knee, connects the femur link and tibia link. Active or passive end effectors can be attached to the free end of each tibia link depending upon the terrain and type of alternative mobility desired. Each leg operates in its respective plane, each of which contains the centerline of the central body Each hip and knee joint is powered by an actuator that is capable of causing or resisting rotation of the joint. The angular position velocity, acceleration, and torque of the joints are logic controlled The platform requires only three sets of two actuators and three sets of two moving links to generate complex motions with a high degree of mechanical reliability.

Although SKITTER is mechanically simple in nature, the platform's control schemes can become quite complex. However the complexity lies in the governing control algorithms and

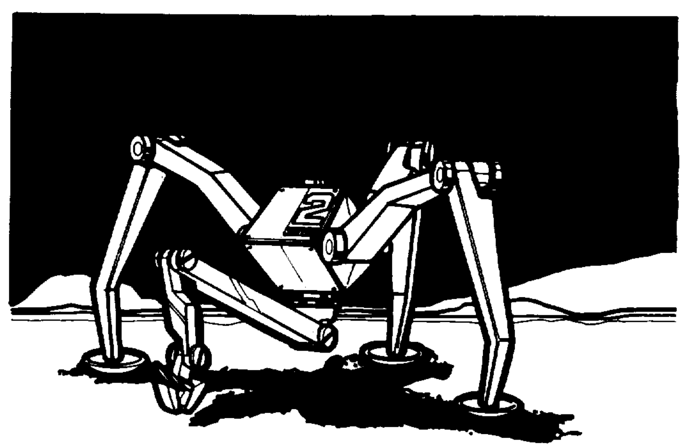


Fig. 1. SKITTER. Illustration courtesy of Pacer Works, Ltd., Atlanta Georgia.

support software, which can be easily revised or upgraded to incorporate new technologies. Some of the platform's motions are described below. For a more detailed explanation of the platform motions, refer to *MacLaren and McMurray,* 1988).

Lean

The basic mode of operation for the platform is to reorient its central body or to lean by reconfiguring the legs while always maintaining static stability. One inherent capability of a three-legged platform is that it will be statically stable while all three feet are in contact with the surface and its center of gravity is positioned over the triangle formed by the feet.

Single Step

A simplified step for walking includes pushing off the surface with one foot, reorienting the foot radially and/or laterally while it remains off the surface and using gravity to restore the foot to the surface at a new location. The central body is thus repositioned from its initial configuration. Radial motion of the foot is achieved by an angular change in the raised leg, while tangential motion is achieved by an angular change in the hip and/or knee joints of the legs that remain on the surface.

Jump

SKITTER has the capability of traversing large distances or negotiating small obstacles by using the jump mode sequence. The platform simply leans in the direction of intended travel then reacts its legs in such a way as to cause the platform to jump. One advantage of the jump mode is that the magnitude of directions in which SKITTER can translate is limited only by the possible orientations of the central body; therefore, with proper design, motion in any radial direction can be obtained.

Crutch Walk

SKITTER capitalizes on its inertial characteristics and dynamic stability for translational motion. By sequencing the single step mode of operation, SKITTER can be made to translate in a manner similar to a person walking on crutches. The crutch mode sequence allows the platform to negotiate small obstacles by stepping over them as well as a method for traversing large distances in unknown terrain.

Turning

With the simplest of control strategies, the platform has six preferred radial directions for translation. However, there will be situations that will require the platform to rotate. SKITTER is capable of pivoting about any one of the three feet or, through a sequence of movements, pivot about the centerline of the platform.

The complex motions of the platform enable the mechanical simplification of the implement assemblies. For instance, the central body has the ability to translate along its vertical centerline at any obtainable platform configuration. Therefore, as a drill rig platform, SKITTER eliminates the need for angular positioning and vertical feed mechanisms by leaning to the correct orientation and then raising and lowering itself along the drill string path by a series of coordinated actuator movements. Additonally, SKITTER has the ability to repeat the single step mode for each leg until the central body comes to rest on the surface with the legs extended outward. This particular position, referred to as the squat mode, is advantageous if the platform is being used in conjunction with a lifting device such as a crane boom. In squat mode, the legs form outriggers to counter the moment due to the cargo being lifted, thus eliminating the need for counter weights or other stability mechanisms.

One distinct advantage of the platform is its ability to right itself from an overturned position. The key to this feature is the range of motion of the legs, which can extend above and below the midplane of the central body. For example, if SKITTER landed completely upside down on the surface, the platform could tuck two legs in toward the central body while the third leg pushed against the surface to flip the platform to the correct orientation. The resulting motion is analogous to a person somersaulting and landing on his feet (*Brazell et al.,* 1988a).

Attachments to the mobile platform include many of the devices needed for the construction of a lunar base. The envisioned implements include crane device, drilling apparatus, digging device, and cargo transportation. Each of these devices derives some benefit from the worksite motions of SKITTER (*Brazell et al.,* 1988b).

CURRENT AND FUTURE PROJECTS

The following projects are currently being developed or are envisioned for the future:

1. *Soil engaging implement.* The soil engaging implement, which attaches to the lower platform interface, is a multi-degree-of-freedom robotic arm with a suitable end effector for leveling, trenching, and digging. The attachment causes the platform to be more stable during operation.
2. *Drilling implement.* The drilling implement, which is housed in the central body of the platform, has the capability of core sampling and boring by using dry drilling techniques currently being developed. Platform motions are intrinsic to the operation of the implement for angular positioning of the bit and vertical feed of the drill string.
3. *Lifting implement.* The crane implement, which attaches to the upper platform interface, would accomplish various material handling tasks via a standard interface. Through the use of the platform's squat mode of operation, mass counterbalancing techniques are not required. To facilitate efficient material handling, standardized cargo interfaces are also being developed and tested.
4. *Dual mobility concepts.* Research is currently being conducted to incorporate alternative mobility systems into the SKITTER design. The platform would be more adaptable to varied terrain due to the respective attributes of each type of mobility. Also, assorted mobility systems attached by standard interfaces to the platform increases the reliability of the system for use in remote operations.
5. *Cargo transportation.* Through the use of standardized attachments to the underside of the platform, cargo could be transported on the lunar surface. Interface mechanisms that allow for emergency release of cargo are also being developed.

Following kinematic and dynamic analysis (*MacLaren and McMurray,* 1986), a proof-of-principle model was constructed (*MacLaren and McMurray,* 1987a,b). The purpose of the scale model was to demonstrate different lean positions, obtain and recover from the squat mode, and take a few steps simulating the crutch walk sequence. SKITTER I, which was completely self-contained and weighed approximately 80 lb, was successfully

demonstrated at the NASA/USRA Summer Conference as well as at Kennedy and Johnson Space Centers in 1987. The mobile platform concept was a Grand Prize Winner in the 1987 *Design News Magazine* "Excellence in Design" competition (*Bak,* 1988) and is currently patent pending.

REFERENCES

Bak D. (1988) Three legs make mobile platform. *Design News,* February 15.

Brazell J., MacLaren B., McMurray G., and Williams W. (1988a) A three-legged walker (abstract). In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century,* p. 32. Lunar and Planetary Institute, Houston.

Brazell J., MacLaren B., McMurray G., and Williams W. (1988b) Lunar base construction equipment (abstract). In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century,* p. 31. Lunar and Planetary Institute, Houston.

MacLaren B. and McMurray G., eds. (1986) Control strategy for a three-legged walker. *Georgia Tech. Progress Report 1.* NASA/USRA/University Advanced Design Program, Houston.

MacLaren B. and McMurray G., eds. (1987a) Prototype development of a three-legged walker. *Georgia Tech. Progress Report 2.* NASA/USRA/University Advanced Design Program, Houston.

MacLaren B. and McMurray G., eds. (1987b) Detailed design of a three-legged walker. *Georgia Tech. Progress Report 3.* NASA/USRA/University Advanced Design Program, Houston.

MacLaren B. and McMurray G., eds. (1988) Three-legged walking mobile platform kinematic and dynamic analysis and simulation. *Georgia Tech. Final Report 4.* NASA/USRA/University Advanced Design Program, Houston.

ENGINEERING PLANETARY LASERS FOR INTERSTELLAR COMMUNICATION

N93-14010

Brent Sherwood[1] **and Michael J. Mumma**

Planetary Systems Branch
Laboratory for Extraterrestrial Physics
Greenbelt MD 20771

Bruce K. Donaldson

Department of Aerospace Engineering
University of Maryland
College Park MD 20742

Spacefaring skills evolved in the twenty-first century will enable missions of unprecedented complexity. One such elaborate project might be to develop tools for efficient interstellar data transfer. Informational links to other star systems would facilitate eventual human expansion beyond our solar system, as well as intercourse with potential extraterrestrial intelligence. This paper reports the major findings of a 600-page, 3-year, NASA-funded study examining in quantitative detail the requirements, some seemingly feasible methods, and implications of achieving reliable extrasolar communications.

INTRODUCTION

Current attention on advanced space projects focuses on exploring and settling available planetary bodies, particularly the Moon and Mars. If the next centuries unfold even remotely as contemporary vision projects, a time will come when humans will seek projects beyond the ones we know, to stretch their capacities in ways we can barely predict. Outside our solar system, the universe will always beckon. Completely new kinds of projects to explore it will continue to arise from humanity's growing skills and knowledge—projects that will consume and guide the creative energies of our descendants just as surely as they would mystify and frighten us. Glimpsing some of that future, even through the murky filter of our present skills and knowledge, helps us to know where we might be heading, and why. This paper attempts to outline a novel problem that may occupy our descendants, sketches the kind of space technology they might use to solve it, and pursues the ramifications of their having solved it.

EXTRASOLAR LIFE

For decades people tried to predict the prevalence of extrasolar intelligence using the Drake equation, a product of astronomical, biological, and social probabilities. Depending on assumptions made, the equation posits between 1 and 10^9 advanced civilizations in the Milky Way (*Hart,* 1980), rendering its result academic. Recently, even its underpinning—that life must evolve independently in different stellar systems—has been invalidated theoretically (*Papagiannis,* 1980).

Many schemes have been proposed for interstellar travel (*Dyson,* 1982), opening the possibility of stellar colonization. Using star systems as staging bases, a cultural lineage expanding outward at even the modest rate of one light year per century could sweep the entire galaxy in fewer than 10^7 years, a span only 0.1% of the galactic age (*Papagiannis,* 1980). Diversity of cultural intentions would preclude stopping such a settlement wave, once started (*Hart,* 1980), until it had occupied practically every useful star system in the galaxy (*Turner,* 1985). The absence of verifiable evidence of local colonization suggests that this sudden perfusion of life throughout our galaxy might not have occurred yet. Our own rapid technical progress then makes tenable the possibility that humans might take part in it or even initiate it.

Substantial galactic intercourse among an eventual network of human progeny cultures, or between human and alien cultures (if they exist) would require an ability to communicate across interstellar space at high data transfer rates. Laser beams are particularly suitable for point-to-point links (*Townes,* 1983) and can carry large amounts of data. Interstellar signals generated by infrared (IR) lasers in particular could be detected with useful signal-to-noise ratio (SNR) using contemporary techniques for quantum-limited heterodyne astronomy (*Glenar,* 1981). The work reported here (*Sherwood,* 1988) investigates some options for using IR lasers to establish communication links among neighborhood stars; its goal is to define quantitatively the magnitude and difficulty of the problem of achieving substantive interstellar communication.

THE LINK

A sphere of radius 25 pc (82 ly) centered on the sun encloses 773 approximately solar-type stars (luminosity class V, of spectral types F, G, or K) (*Seeger and Wolfe,* 1985), many more eligible communication targets than any given transmitter could service practically. Yet even at that distance, the far-field spot size required of a point-to-point beam is dominated by the target

[1]Now at JX-23, The Boeing Company, Huntsville AL 35824-6402

dimension desired (Fig. 1), rather than by overall pointing error (given space telescope accuracy) or stellar proper motion uncertainty (known with the forthcoming Astrometric Telescope Facility). Specifying target spots closely concentric with stars, similar in size to the orbits of the terrestrial planets of our solar system, allows high far-field beam brightness. This in turn allows high intercepted signal power for a distant receiver. Infrared extinction by interstellar and circumstellar dust is not a general problem for the target sample.

We presume a pulse-code-modulated binary bit stream, and specify a bit error probability no greater than the 10^{-9} high standard for optical links (*Gowan,* 1984). We presume also a small heterodyne detector with contemporary performance, at the focus of a space-based, 1-km diameter, segmented reflective collector. This receiver is assumed to be stationed in the inner part of the target stellar system, within the central Airy spot of the signal's far-field diffraction pattern. To find and track the signal's Doppler excursions while maintaining high SNR, the receiver must have many reconfigurable, adjacent narrowband channels (extreme examples, depending on the laser transmitter and receiver used, range from 10^4 adjacent 300-kHz channels to $\sim 10^9$ adjacent 3-Hz channels). With these conditions and reasonable assumptions of system efficiencies, a variety of laser types might achieve information transfer to any of our 773 candidate neighbor stars at rates as high as roughly 100 kb/sec. A transfer rate of 100 Mb/sec, approachable if higher bit error probability is allowed, is required for real-time color video transmission.

Achieving such link quality requires a laser signal of high specific brightness, determined by the transmitter design. Configurable reflective transmitter optics can keep the IR signal bright by focusing it closely around the target stars. Subject to photon shot-noise constraints, link quality then becomes a function of the source laser's specific power (W/Hz), a measure of its spectral efficiency. Two extreme options for increasing specific power are either to make a high-power laser, or to operate a moderately

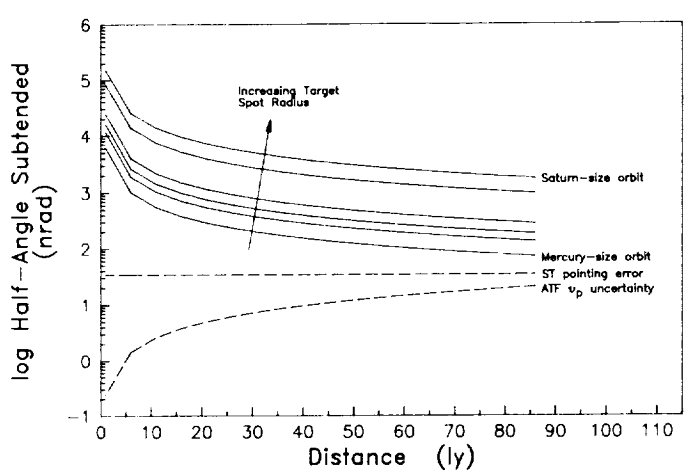


Fig. 1. The beam divergence required to cover distant target orbits exceeds by orders of magnitude the reference angular uncertainties of both pointing ability and star location.

powerful laser with unusually narrow emission linewidth. Either approach might yield a laser signal detectable at great distances with sufficient SNR.

The first method (high power) fits schemes already published for many types of space-based lasers (*Williams and Conway,* 1982), and (as will become clear later) may indeed represent the least cumbersome approach to interstellar communication. A laser practical for this use might be several hundred meters long, be pumped either by nuclear energy, or direct or indirect sunlight (if stationed near Mercury's orbit), and put out about 50 MW. Although power levels orders of magnitude higher than this have been proposed as feasible, serious engineering problems remain unsolved for large space lasers. Notably, cooling the gain medium enough to sustain lasing, cooling the beam optics (passively, to avoid vibration and hence pointing disturbance), and fabricating large IR-transmissive cavity envelopes all represent substantial challenges. Once possible, however, high-power source lasers would have the advantage that many could be emplaced as dedicated transmission stations about any star, linking it effectively and continuously with as many neighboring star systems as desired.

The work reported here, however, investigates in great detail the second method (moderate power), which limits the spectral linewidth of laser emission (*Sherwood,* 1988). This approach would make use of an intriguing resource coincidentally available in our own solar system. Natural CO_2 laser gain has recently been observed (*Deming et al.,* 1983) and modeled (*Deming and Mumma,* 1983) in the mesospheres of Mars and Venus. Its discoverers have suggested that engineered planetary lasers could yield beams of high specific power, useful for deep-space communication (*Deming and Mumma,* 1983).

PLANETARY LASERS

The terrestrial planets of our solar system having atmospheres compositionally dominated by CO_2 (Mars and Venus) support natural stimulated emission in the 10.6 μm and 9.4 μm ro-vibrational bands of the molecule. Collisional excitation and direct solar pumping appear to maintain quantum population inversions in thin mesospheric shells over the daysides of both planets. Although the gain per unit length is small, planetary atmospheres are vast, so that the single pass gain along a tangential path through the subsolar point at the proper altitude of either planet is nominally about 7%, which is comparable to single pass gain through laboratory laser gain media (*Deming and Mumma,* 1983). Inducing laser oscillation to yield a usable output beam by configuring an optical resonator around such a planet then constitutes a novel problem in advanced space system design.

The available peak single-pass gain shrinks with a cosine dependence as the path's tangent point moves around the planetary sphere away from the subsolar point, and vanishes on the darkside (*Deming and Mumma,* 1983). Since the line of sight defined by any pair of orbiting satellites cannot be stationary with respect to the subsolar point, resulting gaps in system gain could be filled in by establishing multiple reflectors as a ring resonator around the planet. Continuous oscillation might then occur. The net gain would increase as more satellites were added, with a smoother first-order envelope for odd-sided polygonal resonators (Fig. 2). A pentagon provides both these benefits while still limiting both system size and low-altitude gravitational and drag perturbations on the resonator satellites. The continuously available effective single-circuit steady-state gain then amounts to at least 10% for either Mars or Venus.

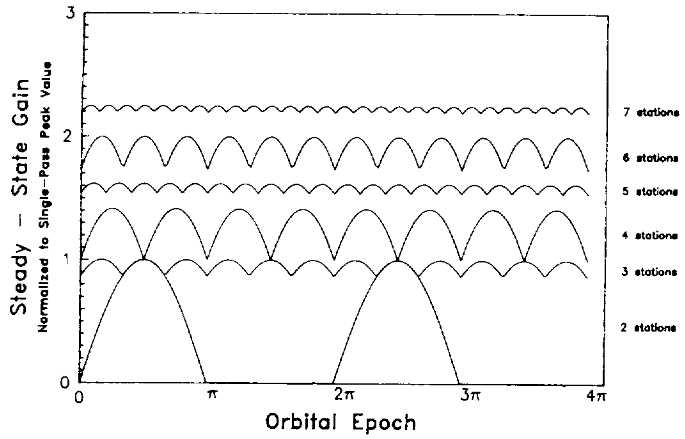


Fig. 2. The single-circuit steady-state gain available from a lossless planetary laser resonator is better for odd-sided, higher-order polygon geometries.

However, Mars and Venus provide strikingly different environments for operating an orbital laser resonator. Mars's orbital eccentricity (0.0934) causes a 39% annual variation in insolation and hence in available laser gain. A sun-synchronous resonator orbit, enforced by Mars's oblateness to pass over the subsolar region at all times throughout the martian year, is the only orbit that does not compound the annual gain variation with further seasonal cycles. However, such an orbit also overflies the entire martian surface, the spectacular geography of which produces the bumpiest gravity field known among planets (*Balmino et al.,* 1982). The altitude variations alone experienced by satellites in a pentagonal resonator formation might be as large as 50 km over a timescale of only 20 min. Since the inversion layer through which the laser line of sight must pass is only about 10 km thick (*Deming and Mumma,* 1983), operating a planetary laser continuously at Mars would pose a serious dynamical problem.

By contrast, Venus is extremely spherical, smooth, and benign. With a slow rotation rate (its day exceeds its year) and large mass, it is the most spherical planet known. Fully 60% of its mapped surface lies within 500 m of its modal radius (*Pettengill et al.,* 1980) and because its topography is largely isostatically compensated (*Masursky et al.,* 1980), gravitational bumpiness is limited mainly to continental margins. Satellites at the pentagonal altitude for Venus would experience radial departures of less than 2.2 km and tangential departures of less than 700 m from their nominal Keplerian orbit, allowing them to sustain continuously a cavity beam as large as 5 km in diameter. Venus's obliquity is only 3°, so an essentially equatorial orbit plane always contains the subsolar point. And the planet's orbital eccentricity is only 0.0067, so the available gain varies by less than 3% annually. Finally, Venus space is much more likely to remain unpeopled—and uncontaminated—than Mars space. For all these reasons, Venus is the better site for positing planetary laser operation.

Extracting a useful output beam from a large orbiting planetary resonator would be facilitated if the cavity were not strictly a ring laser. The laser topology considered here is instead that of a more conventional linear oscillator wrapped around the planet so that its "ends" are adjacent, but separate, at one vertex of the pentagon. The tangent points for maximum mesospheric gain are 130 km above Venus, so the pentagonal resonator orbit altitude is 1589 km (Fig. 3). For lasing to occur, the coherence length of an intracavity electromagnetic field must exceed the double-pass cavity length, which in this case is 90,000 km, several orders of magnitude greater than any laser coherence length yet demonstrated. Since the inverse of the field's coherence time is its oscillation linewidth, achieving oscillation in a planetary-sized resonator would dictate extremely narrow spectral emission (less than 3.3 Hz for the venusian pentagon) (*Sherwood,* 1988).

While such extreme spectral purity would yield the high specific power needed for substantive interstellar communication, sustaining laser oscillation over planetary dimensions constitutes a technological challenge of unprecedented scale. The toughest technical problem involved (autonomous, simultaneous, precise, optomechanical control distributed and coordinated around a planet) would completely drive any planetary laser design. However, virtually all the component problems that this challenge combines must be solved anyway in the separate contexts of other large space projects already envisioned for the next century. Applying rigorous spacecraft systems synthesis to a set of emerging and demonstrated advanced technologies is the only means available to explore the ultimate feasibility of engineered planetary lasers.

A REFERENCE DESIGN

To pursue the details of engineered planetary lasers, and expose quantitatively the critical technology advances required to make one work, we now outline one possible type of venusian laser transmitter for interstellar signaling at rates up to 1 kb/sec. This reference system consists of 13 spacecraft distributed throughout Venus space; linked by dedicated laser telemetry, they act cooperatively as one device. The craft are divided functionally into three teams: six make up a split-ring pentagonal resonator with a 1-km diameter laser cavity; three others work as a switch to focus and steer the emergent beam, and two teams of two craft each alternate in impressing the beam with a program signal and aiming it toward target stars. All use a common subsystem vocabulary, all are assembled in Venus space, and all are serviced robotically.

Figure 4 shows the labeled resonator configuration. The optical surfaces defining the cavity must "ride" the beam in phase at all times, with drift rates less than 2 μm/sec, if the laser is to oscillate coherently. The cavity path length cannot change except by multiples of the lasing wavelength (called cavity mode hopping). To ensure this, each reflector must be positionable with 60 nm relative accuracy. The reference planes describing the ideal positions and angles of all six cavity reflectors change continuously, as especially thermal and gravitational perturbations vary with orbital anomaly. The immense challenge of operating the planetary laser is, at core, one of updating those reference planes and matching them with real hardware at all times. All spacecraft systems in the fleet resonator exist only to support that function.

Huygens' principle allows fragmenting the problem of kilometer-scale diffraction-limited optical apertures, thereby shifting most of the technical difficulty from materials to control. The reflector surfaces of the 95,000-MT Basic Vertex Stations 2, 3, 4, and 5 (Fig. 5) are elliptical, segmented arrays of 230,000 3-m hexagonal, honeycombed beryllium (*Paquin et al.,* 1984) gold-faced mirrors. Each is isolated from and positioned relative to the spacecraft bus with a resolution of nanometers by three electromagnetic translators (EMTs) (*Sielman and Balsarowicz,* 1984), allowing three-DOF mirror pointing control. The bus

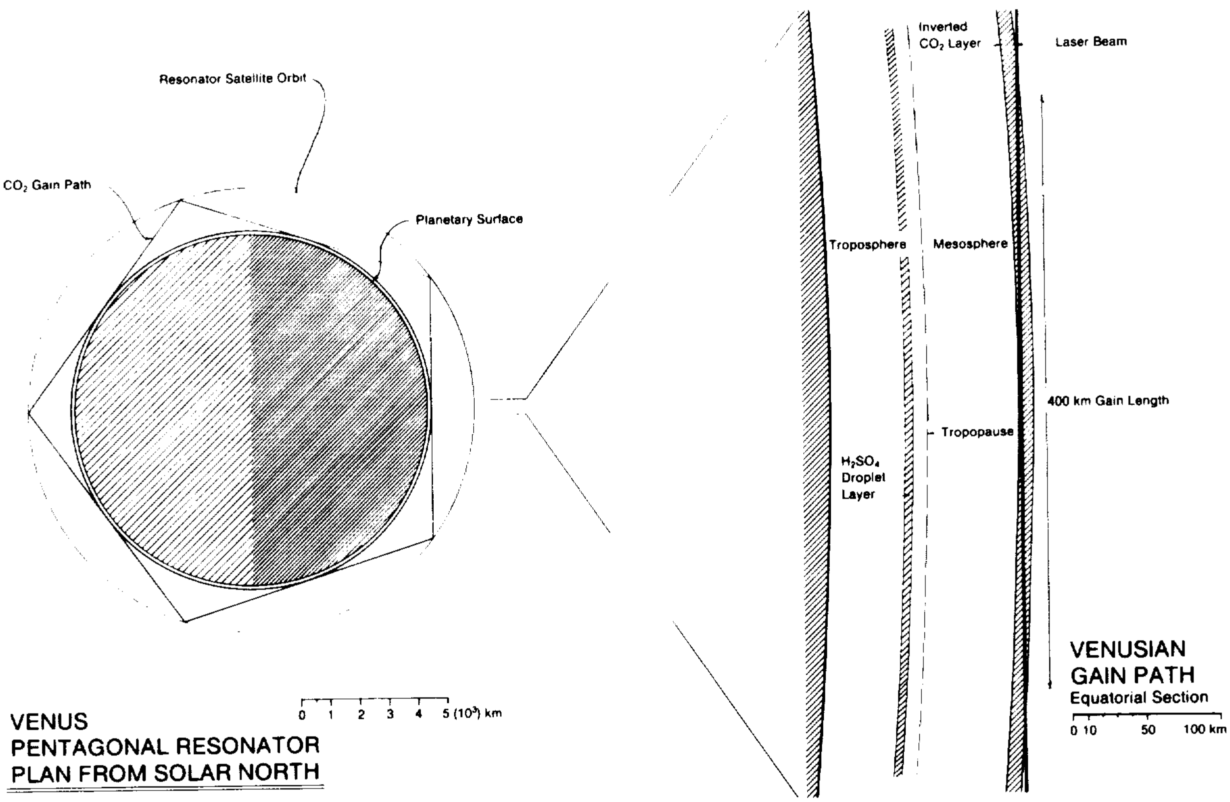


Fig. 3. The pentagonal-resonator orbit altitude and active gain length are determined by inversion conditions at Venus.

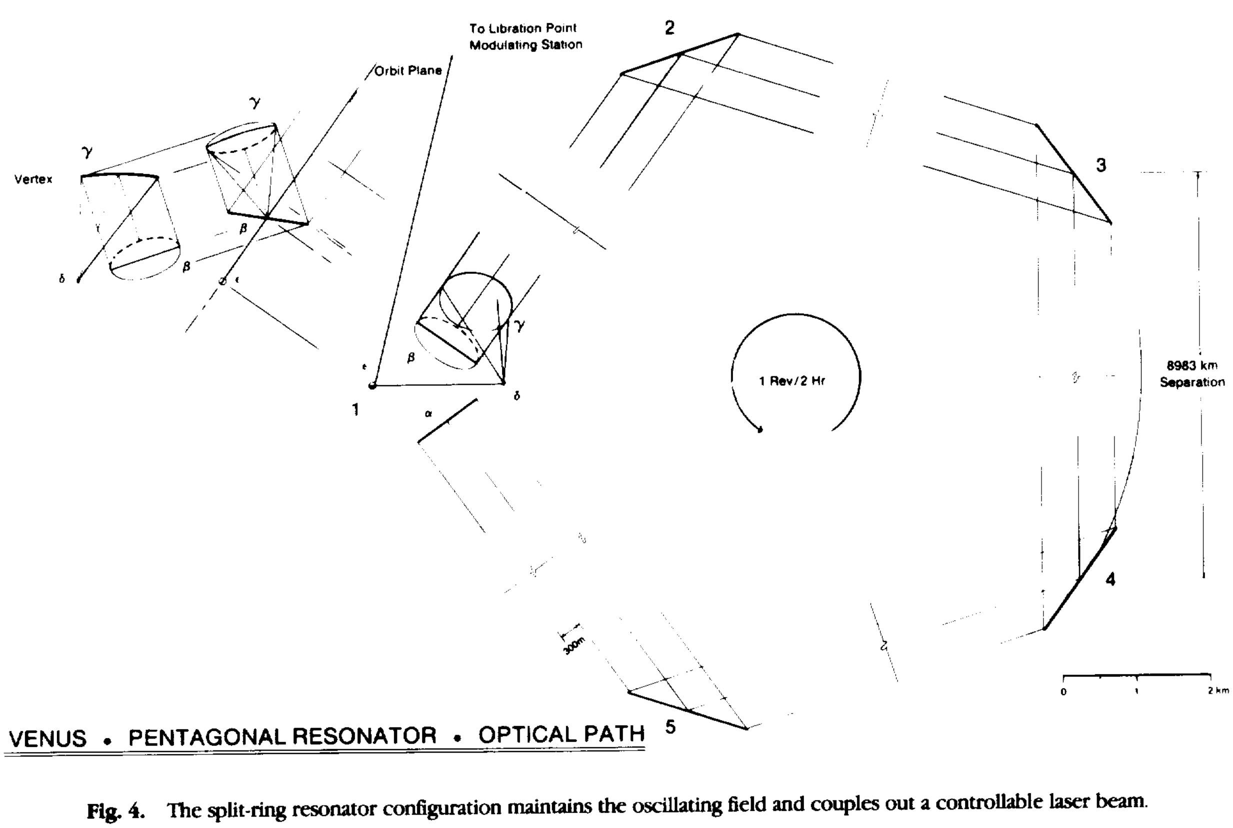


Fig. 4. The split-ring resonator configuration maintains the oscillating field and couples out a controllable laser beam.

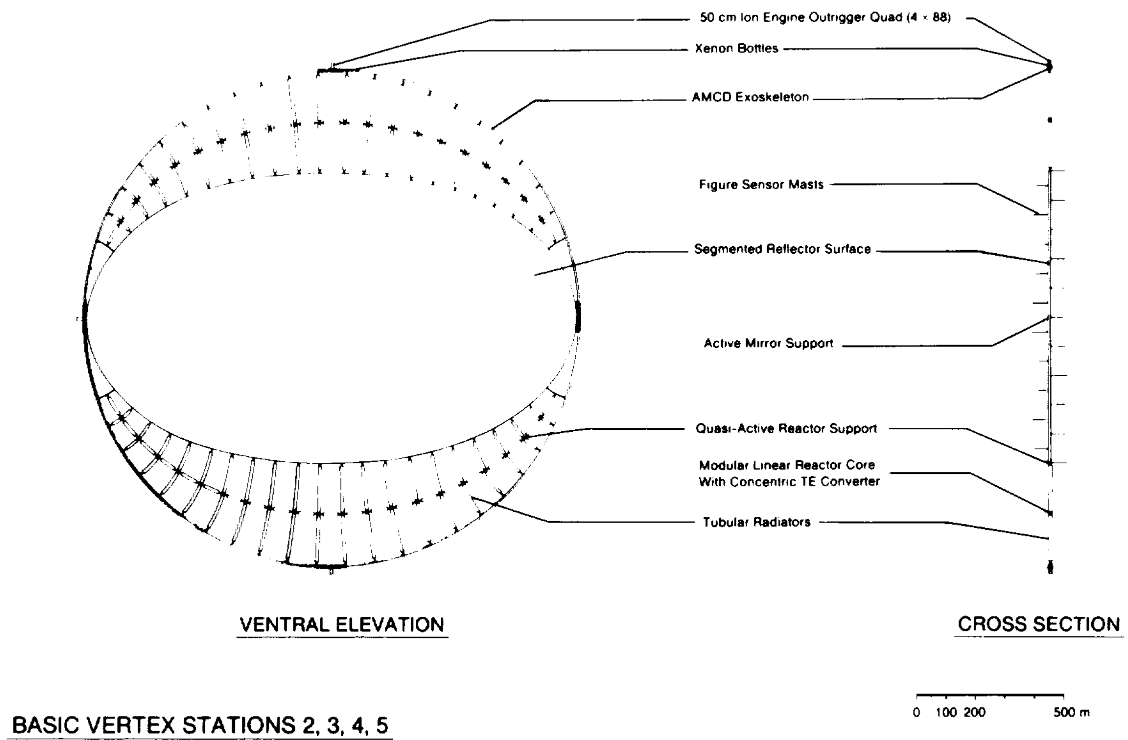


Fig. 5. The basic vertex stations are large, actively flat mirror satellites.

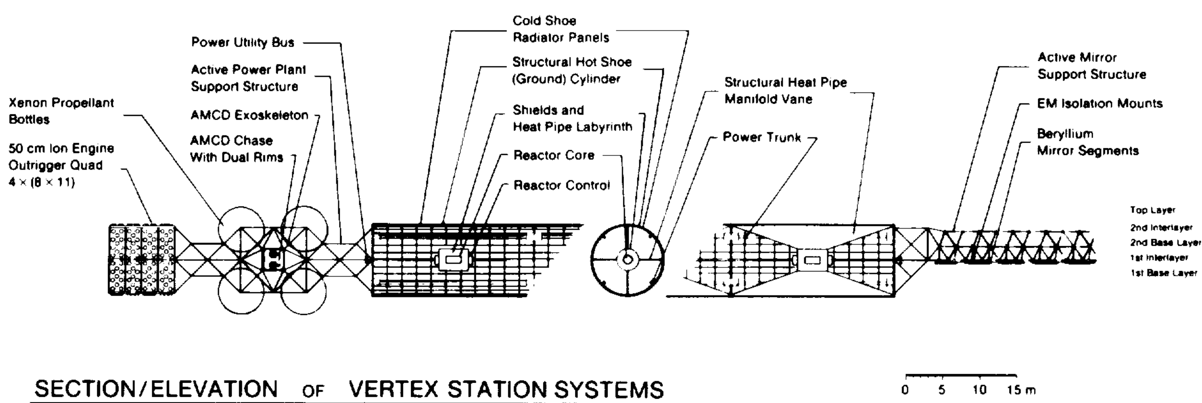


Fig. 6. The spacecraft systems are selected for energy-efficient, long-life, vibrationless, redundant performance.

structure itself (Fig. 6) is built up of active truss members, C/Mg composite (*Remondiere et al.,* 1985) tubes whose extension, bending, and vibration behavior are monitored with nanometer resolution by embedded fiberoptic strain and temperature sensors (*DePaula et al.,* 1987), and actively controlled with submicrometer resolution by fast piezoelectric (PZ) surface films (*Studer et al.,* 1986) and slow thermal actuators (*Haftka and Adelman,* 1985). This backup structure provides a responsively stiff reaction ground for mirror segment actuation.

An overlapping hierarchy of short-range optical sensors provides intersegment alignment data across the expanse of each reflector surface, and differential interferometry (*Hewitt,* 1984) provides phase data about the stations' relative positions. Dedicated laser-telemetry links the resonator craft, providing each with state data on the others at the 6-Hz interactive rate constrained by lightspeed delay around the pentagonal ring. Coordinating all these data to generate the actuator commands necessary for sustaining laser oscillation poses the ultimate problem of the fleet system, on which hinges the feasibility of operating a planetary laser (*Sherwood,* 1988).

No contemporary, artificial computational technology can come close to the required performance. The fleet controller must process on the order of 10^9 widely distributed signals simultaneously within milliseconds, despite component failures, a changing

perturbation environment, and the inescapable 6-Hz verification limit. Hence it must compensate predictively, based on an adaptive capacity to learn in detail the repetitive disturbances of its orbit and its own past performance, refining its commands over time (*Sherwood*, 1988).

An ancient precedent for processing complexity far beyond even these needs is vertebrate neurophysiology (*Kent*, 1981). Artificial intelligence (AI) progress in modeling and duplicating neuronal interaction, albeit nascent, is sufficiently successful and accelerating (*NASA*, 1988) to warrant positing its eventual application to problems of this type. The fleet controller can then be projected to be a massively parallel, adaptive, optical (*Fisher*, 1983) neural net (*NASA*, 1986) distributed throughout all the fleet systems to monitor and govern precisely their mechanical behavior.

The housekeeping systems (Fig. 6) are selected for their smooth, vibration-free operation as well as economical logistics. Overall spacecraft attitude is trimmed by annular momentum control devices (AMCDs), which are dual, magnetically suspended, thin Kevlar rims circumscribing the entire spacecraft. Counter-rotating at high speed, they effect three-axis control maneuvers by slight differential tipping and speed changes (*Anderson and Groom*, 1975). The debris-shielded AMCD chases are maintained circular by an active exoskeleton truss, their control hardware positioned within micrometer tolerances by PZ mountings. Overall station-keeping propulsion and momentum desaturation occur via ganged xenon-ion engines. Each craft is tanked with a replaceable 10-year propellant supply (about 17,000 MT for the entire fleet), based on disturbance forces including solar pressure and gravity, and exospheric drag. Modular thermoelectric (TE) fission power plants (*El-Genk and Hoover*, 1985) supply about 400 MW to run the control, propulsive, structural, and nervous systems of each station.

The two cavity "end" reflectors, 1α and 1β, are much the same as Stations 2, 3, 4, and 5, but somewhat smaller due to their unique incidence angles (Fig. 4). Not being principal-axis planet oriented, and therefore subject to large, constant gravity-gradient torques, these two reflector craft are braced against each other structurally. The gold mirror surfaces of 1β are etched as a blazed diffraction grating with 11.68-μm ruling, and 1β itself is oriented in the Littrow configuration. This simultaneously limits cavity oscillation to the lowest-threshold (P12) line of CO_2 (wavelength 10.513 μm), and diffracts 2% (180 kW) of the circulating s-plane polarized laser light out of the orbit plane to reflector 1γ, which focuses the output beam back up into the orbit plane onto 1δ, which, in turn, undoes most of the beam's convergence and relays it up to 1ϵ tethered above (Fig. 7). Then 1ϵ uses two pivoting mirrors to send the 10-m diameter intermediate beam alternately to one of the twin final stations. Concentrating the intermediate beam (at 2300 W/m^2 almost as strong as venusian sunlight) allows 1δ, 1ϵ, and all subsequent craft in the fleet to mass less than a thousandth as much as the vertex stations, and to consume about a thousandth as much power.

The final stations are fixed in Venus space at the planet's collinear Lagrange libration points, L1 and L2. From the near-equatorial resonator orbit, 1ϵ can always see one or the other of these stations, allowing an essentially continuous transmission duty cycle to any star. The reference transducers (Fig. 8) monitor

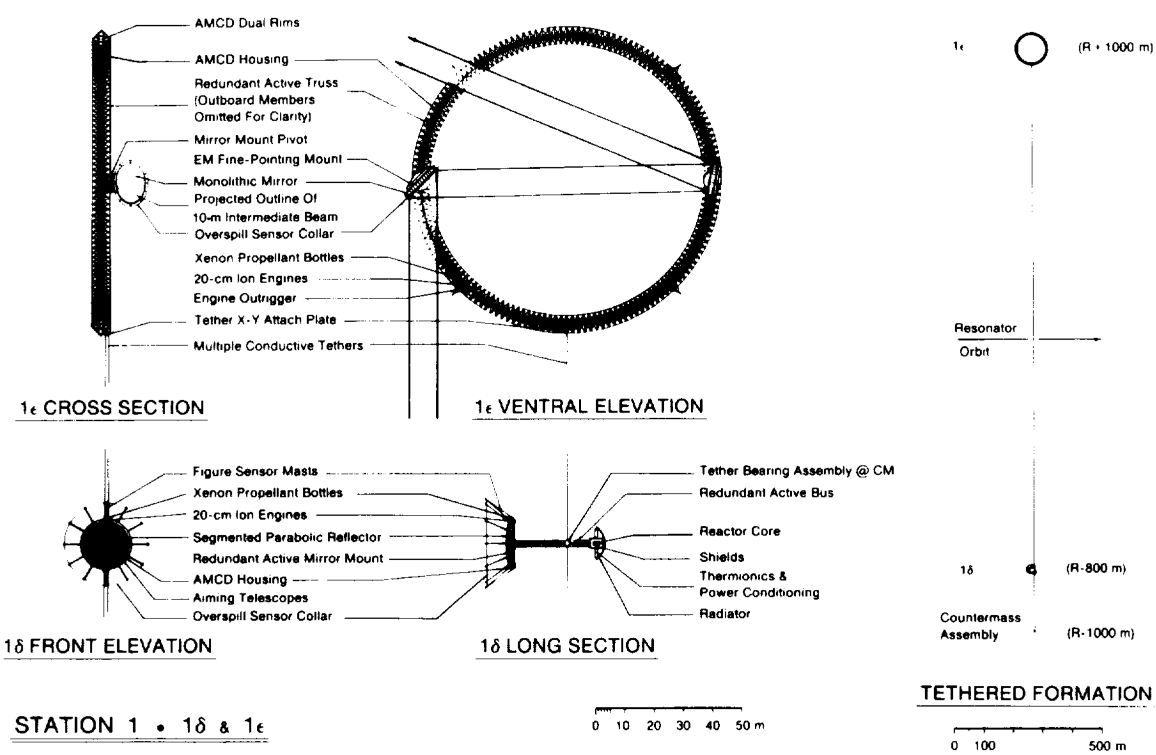


Fig. 7. The switching satellites control focus and direction as the laser beam leaves the resonator orbit.

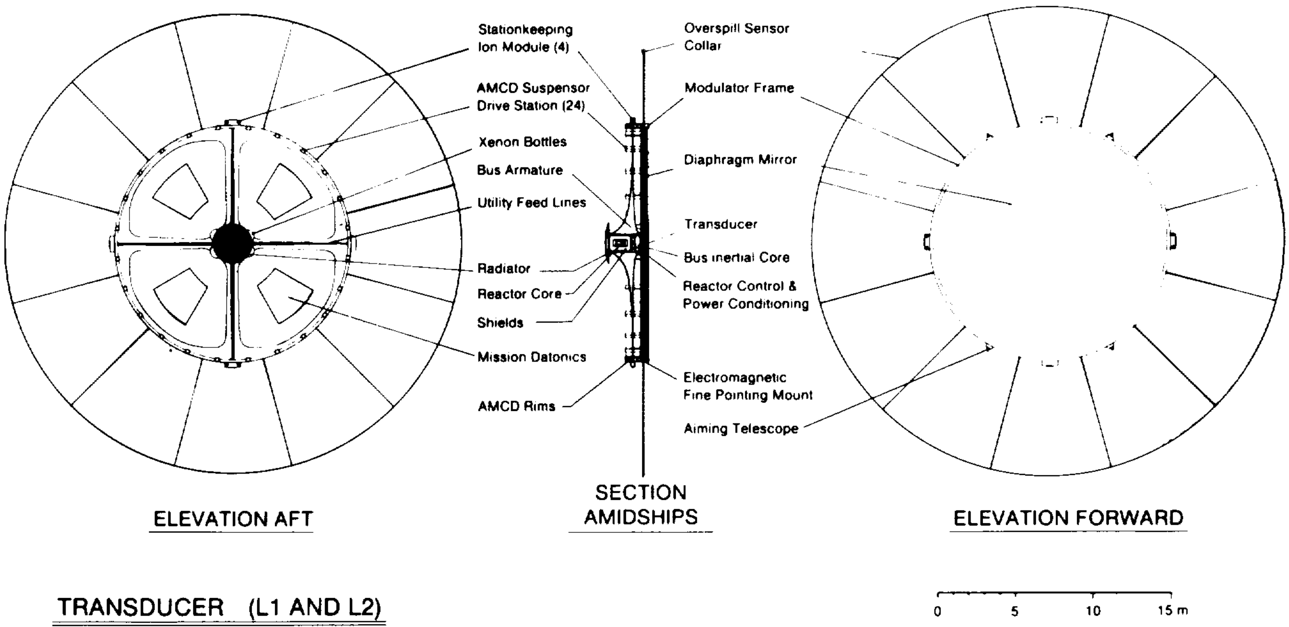


Fig. 8. Three-axis-stabilized transducer satellites modulate and target the interstellar laser beam.

the 21% of the diffracted intermediate beams they receive from Venus, apply corrective pointing and focusing biases, and modulate it electromechanically with deformable membrane mirrors. More advanced transducers using microwaveguide modulation (*Liu*, 1986) might accommodate mission signals at rates much faster than 100 kb/sec, up to the 100 Gb/sec contemporary signal processing limit. Aiming at targets in the celestial hemisphere behind either transducer requires a final reflection, provided by its associated ring (Fig. 9).

The reference planetary laser just outlined represents the first attempt to bring current understanding of imminent technologies to bear in a rigorous, integrated way on the advanced problem of substantive interstellar communication. We intend the outline not as a polished "solution," but rather as the seed of a problem worth solving. Even if the technical difficulties become tractable, emplacing and operating any system for such transmission would prove a formidable undertaking. Application of current costing methods to the project, though, is a misleading exercise. Rather, asking for what kind of society the project would consume only 1% of the gross economic product, reveals its proper context. That would be a mature interplanetary culture already competent at sophisticated spacecraft control, interorbital transport, resource mining from lodes distributed throughout the inner solar system, and microgravity and vacuum industries. Our own society will be heading toward those capabilities in the next century.

THE LIMIT

Augmenting the planetary laser reference design (increasing the cavity beam diameter to 5 km, collecting more of the diffracted beam at the Lagrange point stations, and bringing receiver degradation closer to theoretical limits) would make its spectrally narrow signal even more useful by increasing received power. Other advances [in high-power nonplanetary space lasers, optical processing, and modulation techniques (*Manneberg et al.*, 1987)] might improve transfer rates for communication systems well beyond the 10-Gb/sec limit of current data processing speeds. The result could be an interstellar link capable, with practically arbitrary bit reliability, of supporting data transfer rates as high as the IR carrier frequency could ever allow (*Sherwood*, 1988), on the order of the Tb/sec (Fig. 10).

If large lasers can establish substantive communication channels among neighboring stars, cultures operating them would have available an unprecedented bridge across the astronomical distances of interstellar space. Should our own society ever achieve the necessary spacefaring skills and economy, we would by that time probably have other technologies that we are already developing, such as molecular engineering, well in hand. To identify what kind of future such tools might forge, we outline the possibly inevitable consequences of combining these advanced capabilities. Having seen fire, could we predict rocket engines? Having split the atom, did we predict nuclear arms negotiations? Where, then, might interstellar communication lasers lead?

If interstellar information transfer at rates as high as the 10^{20} b/yr just discussed is possible, complex instructions could be sent reliably to distant receivers configured upon arrival by small, human-launched, photonically propelled (*Forward*, 1984) interstellar probes. If nanotechnological assembly, computation, recording, and biostasis (*Drexler*, 1986) become available, such probes could then process local material resources according to those transmitted instructions. A civilization possessing these tools might use them to transmit complex datasets directing remote

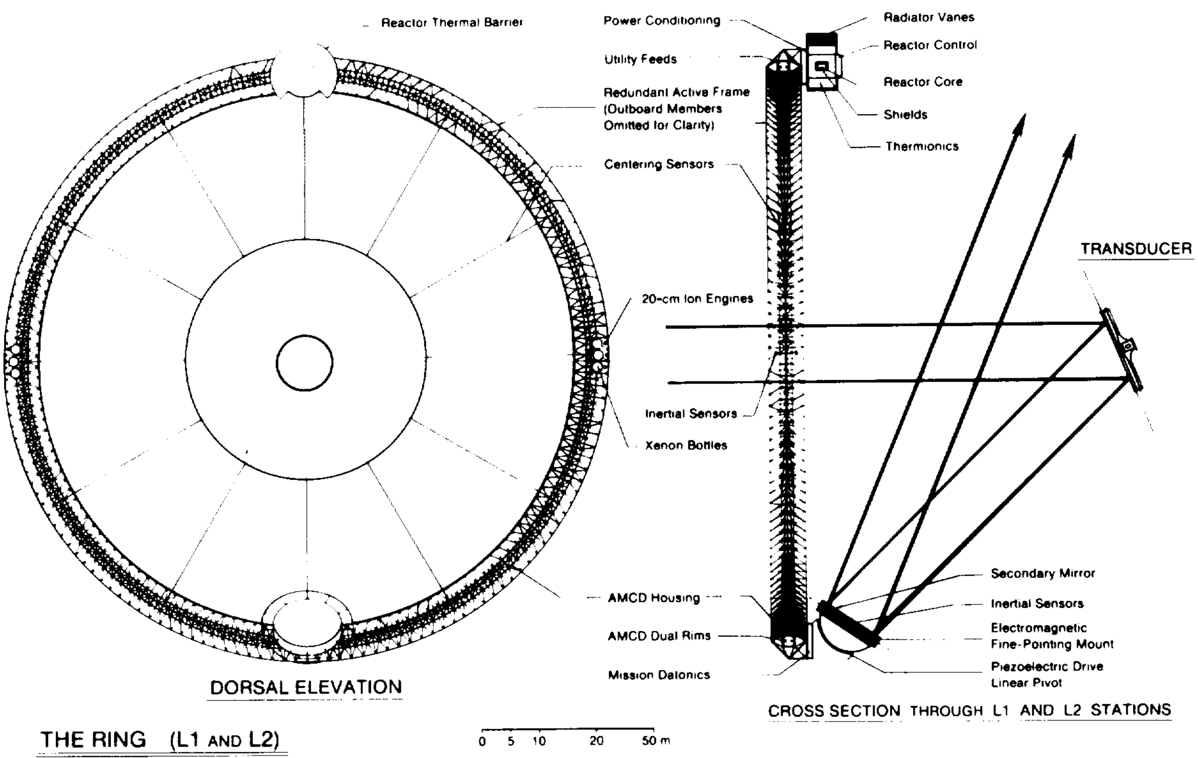


Fig. 9. A final reflection allows targeting the entire celestial sphere.

nanoassembly of the unique molecular structure of their bodies and brains (*Sherwood,* 1988). This ability would amount to interstellar transportation through cloning. Adding efficient deep-space communication by high-power lasers to nanotechnology could then lead to a future of direct interstellar travel, thus reducing greatly the time required for human progeny to colonize the galaxy.

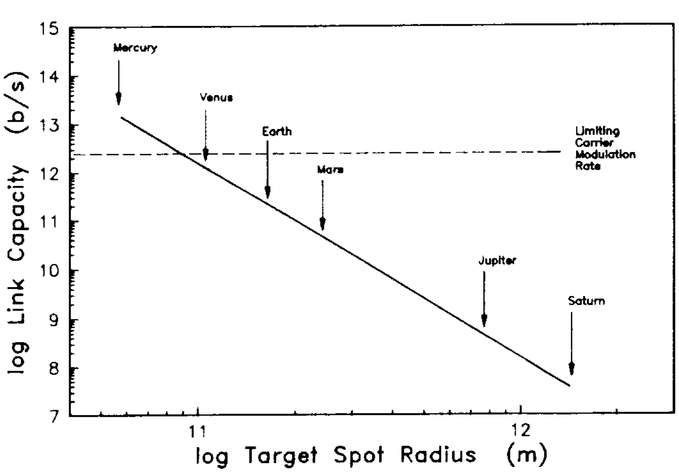


Fig. 10. Given advanced modulation techniques, nonplanetary high-power lasers could allow extremely high-rate communication between stellar targets.

Acknowledgments. The work reported here was made possible by grant NGT 21-002-823, through the NASA Graduate Student Researchers Program.

REFERENCES

Anderson W. W. and Groom N. J. (1975) *The Annular Momentum Control Device (AMCD) and Potential Applications.* NASA TN-D-7866. 36 pp.

Balmino G., Moynot B., and Vales N. (1982) Gravity field model of Mars in spherical harmonics up to degree and order eighteen. *J. Geophys. Res., 87,* 9735-9746.

Deming D. and Mumma M. J. (1983) Modeling of the 10-μm natural laser emission from the mesospheres of Mars and Venus. *Icarus, 55,* 356-368.

Deming D., Espenak F., Jennings D., Kostiuk T., Mumma M., and Zipoy D. (1983) Observations of the 10-μm natural laser emission from the mesospheres of Mars and Venus. *Icarus, 55,* 347-355.

DePaula R. P., Moore E. L., and Jamieson R. S. (1987) Overview of fiber-optical sensors. TSP in *NASA Tech. Briefs, 11,* Item 84. Associated Business Publications. 14 pp.

Drexler K. E. (1986) *Engines of Creation.* Anchor, Garden City, New York. 298 pp.

Dyson F. (1982) Interstellar propulsion systems. In *Extraterrestrials: Where Are They?* (M. H. Hart and B. Zuckerman, eds.), pp. 41-45. Pergamon, New York.

El-Genk M. S. and Hoover M. D. (1985) *Space Nuclear Power Systems.* Orbit, Malabar, Florida.

Fisher R. A., ed. (1983) *Optical Phase Conjugation.* Academic, New York. 594 pp.

Forward R. L. (1984) Roundtrip interstellar travel using laser-pushed lightsails. *J. Spacecr. Rockets, 21,* 187-195.

Glenar D. A. (1981) *Development of Diode Laser Heterodyne Spectrometer and Observations of SiO in Sunspots.* NASA TM-83902.

Gowan J. (1984) *Optical Communication Systems.* Prentice-Hall, Englewood Cliffs, New Jersey.

Haftka R. T. and Adelman H. M. (1985) An analytical investigation of shape control of large space structures by applied temperatures. *AIAA J., 23,* 450-457.

Hart M. H. (1980) N is very small. In *Strategies for the Search for Life in the Universe* (M. D. Papagiannis, ed.), pp. 19-25. Reidel, Dordrecht, Holland.

Hewitt P. L., ed. (1984) *Modern Techniques in Metrology,* pp. 122-157. World Scientific, Singapore.

Kent E. W. (1981) *The Brains of Men and Machines.* McGraw-Hill, New York.

Liu P.-L. (1986) Surface wave electro-optic modulator. *SPIE 716 High Frequency Optical Communications,* pp. 58-61. Society of Photooptical Instrumentation Engineers.

Manneberg G., Kull M., and Lindquist S.-E. (1987) An all-optical amplifier for terahertz AM signals: A proposal. *J. Lightwave Technol., LT-5,* 236.

Masursky H., Eliason E., Ford P. G., McGill G. E., Pettengill G. H., Schaber G. G., and Schubert B. (1980) Pioneer Venus radar results: Geology from images and altimetry. *J. Geophys. Res., 85,* 8232-8260.

NASA (1986) *Frontiers of Massively Parallel Scientific Computation.* NASA CP-2478. 321 pp.

NASA (1988) *NASA Tech. Briefs, 12(1),* entire issue. Associated Business Publications, New York. 110 pp.

Papagiannis M. D. (1980) The number N of galactic civilizations must be either very large or very small. In *Strategies for the Search for Life in the Universe* (M. D. Papagiannis, ed.), pp. 45-57. Reidel, Dordrecht, Holland.

Paquin P. A., Levenstein H., Altadonna L., and Gould G. (1984) Advanced lightweight beryllium optics. *Opt. Eng., 23,* 157-158.

Pettengill G. H., Eliason E., Ford P. G., Loriot G. B., Masursky H., and McGill G. E. (1980) Pioneer Venus radar results: Altimetry and surface properties. *J. Geophys. Res., 85,* 8261-8270.

Remondiere O., Pailler R., Momode A., and Roy Ph. (1985) Magnesium matrix composite materials processing and applications. In *Proc. 1st European Conf. on Composite Materials and Exhibition,* pp. 732-737.

Seeger C. L. and Wolfe J. H. (1985) SETI: The microwave search problem and the targeted search approach. In *The Search for Extraterrestrial Life: Recent Developments* (M. D. Papagiannis, ed.), pp. 391-395. Reidel, Dordrecht, Holland.

Sherwood B. (1988) *Engineering Planetary Lasers for Interstellar Communication.* NASA CR-180780. 589 pp.

Sielman H. and Balsarowicz A. (1984) Electromechanical tuning element with extended range for dither stabilization of lasers. *Rev. Sci. Instrum., 55,* 1551-1555.

Studer P., Baz A., and Sharma R. (1986) Actuators for actively controlled space structures. *SPIE 641 Acquisition, Tracking, and Pointing,* pp. 148-159. Society of Photooptical Instrumentation Engineers.

Townes C. H. (1983) At what wavelengths should we search for signals from extraterrestrial intelligence? *Proc. Natl. Acad. Sci. USA, 80,* 1147-1151.

Turner E. L. (1985) Galactic colonization and competition in a young galactic disk. In *The Search for Extraterrestrial Life: Recent Developments* (M. D. Papagiannis, ed.), pp. 477-482. Reidel, Dordrecht, Holland.

Williams M. D. and Conway E. J., eds. (1982) *Space Laser Power Transmission System Studies.* NASA CP-2214. 209 pp.

UNIT OPERATIONS FOR GAS-LIQUID MASS TRANSFER IN REDUCED GRAVITY ENVIRONMENTS

N93-14011

Donald R. Pettit

Los Alamos National Laboratory
Los Alamos NM 87545

David T. Allen

Department of Chemical Engineering
University of California
Los Angeles CA 90024

Basic scaling rules are derived for converting Earth-based designs of mass transfer equipment into designs for a reduced gravity environment. Three types of gas-liquid mass transfer operations are considered: bubble columns, spray towers, and packed columns. Application of the scaling rules reveals that the height of a bubble column in lunar- and Mars-based operations would be lower than terrestrial designs by factors of 0.64 and 0.79 respectively. The reduced gravity columns would have greater cross-sectional areas, however, by factors of 2.4 and 1.6 for lunar and martian settings. Similar results were obtained for spray towers. In contrast, packed column height was found to be nearly independent of gravity.

INTRODUCTION

Unit operations are the basic elements of chemical processes to perform mass transfer between gas and liquid phases. Gas-liquid mass transfer is the process of transporting a chemical species from one of the phases into the other. Unit operations for gas-liquid mass transfer have a mature technological base. These terrestrial-based industrial processes range from the manufacture of gasoline and petrochemicals to sewage treatment and the making of pharmaceuticals.

When humans build lunar and martian bases, harsh foreign environments will require a high degree of technical support for development. Technologies will be needed to maintain and recycle life support, process local resources into fuels and construction materials, and to manufacture goods for trade and economic independence. Integral to these processes is the need to perform species separations between gases and liquids, hence the need for unit operations. Several products can be made from indigenous resources for lunar and martian bases (*Mendell,* 1985; *Duke,* 1986). Although chemical processes have been proposed for manufacturing on the Moon and Mars, the details of gas-liquid unit operations have largely been ignored. The volume, mass, and resource consumption rates of the process equipment are crucial in development of overall mission strategies, especially if the equipment is brought from Earth. Estimating equipment mass and volumes directly on Earth-based designs could be erroneous. The purpose of this work is to use simple scaling rules and dimensional analysis to scale an Earth-designed unit operation for use in reduced gravity. It is important to point out that scaling is used to give a first-order design in the absence of actual experimental data taken in low gravity. Until such data are available, scaling gives estimates in the design, and determines equipment volumes and masses.

STANDARD GAS-LIQUID UNIT OPERATIONS

Mass transfer ultimately hinges on diffusional transport of chemical species between the fluid phases and this, in turn, requires a large interfacial surface area. Since diffusion is typically a slow process, the desired path length over which diffusion occurs is made short. Turbulence provides fast convective transport and is usually incorporated to move species from the interior or bulk of the fluid to the interface where molecular diffusion takes place.

There are many ways to achieve the conditions for efficient mass transfer, and the advantages of each method can be matched to the diffusional properties of the species of interest. Dispersing the gas into the liquid as small bubbles in bubble columns provides a large interfacial surface area. Diffusion within the short path length of the bubble brings the species to the interface where the surrounding liquid is well mixed and turbulent, and efficiently transports the species from the interface to the liquid bulk. Liquid can be dispersed into the gas as small droplets in spray towers, providing a large interfacial surface area. Diffusion within the drop brings the species to the interface where turbulence convects it away to the gas bulk. On Earth, convection and related gravitation effects play a significant role in these processes; the effect of lunar and martian gravity is yet to be demonstrated and currently their effects have to be scaled from their known behavior on Earth.

The choice between these two contacting schemes hinges on where the dominant diffusional resistance lies. To counteract dominant resistance in the liquid phase (i.e., a small diffusion coefficient), bubble columns are used where convective transport prevails in the liquid and diffusion is in the gas. Dissolving oxygen into water for aerobic microbial processes falls in this category,

hence bubble columns are a standard contacting method. Systems with the dominant resistance in the gas phase benefit by dispersing the liquid as droplets in spray towers where convection is in the gas. Evaporating water into air for humidification and cooling is a system where the dominant resistance lies in the gas phase and spray towers are a standard contact method.

Another standard contacting method is to use a packed column. A containing vessel is packed with small complex-shaped objects that present a large surface area and long tortuous passages. The containing vessel is generally a large vertical pipe; however, much smaller, rotating containment vessels have been used. For the vertical pipe configuration, the liquid is distributed on the top and percolates downward as a thin film that coats the packing material. Gas is blown upward in turbulent flow through the tortuous passages. Efficient mass transfer is achieved because of the large interfacial area, the turbulent convection in the gas, and the thin falling film in the liquid. In rotating contactors, liquid enters at the center of the disk-shaped device and flows radially, due to centrifugal force, to the outer edge of the device. Gas flows either in the same direction as the liquid (cocurrent) or in the opposite direction (countercurrent). These rotating contactors lower resistance in the liquid phase by making the film covering the packing material extremely thin. Either type of packed column is suitable for mass transfer when either or both phases have high resistances.

Other factors are important as well as the efficiency of mass transfer. Some systems tend to foam, so dispersing bubbles in liquid creates a large foamy head and requires centrifugal foam breakers or a large dead space to allow for the head volume. Systems with sediment or fast-growing microorganisms tend to plug the passages in packed columms. Spray towers are often inconveniently high to allow sufficient contact time while the droplets are falling. Choosing the best contacting scheme for a given mass transfer operation involves the consideration of many variables, often resulting in a compromise in mass transfer efficiency to alleviate other troublesome effects. Unit operations that are optimized for Earth can be scaled for use in the reduced gravity environments found on the Moon and Mars and is the subject of this paper. Some thought should be given to ascertain whether a nonstandard contacting method might be better. For example, spray towers that would be impractically high on Earth might be very practical on the Moon due to the ⅙ gravity slowing the rate of droplet descent.

SCALING FOR REDUCED GRAVITY

These unit operations require gravitational forces to separate the gas and liquid phases. Modifications to the equipment will be necessary for operation in reduced gravity. Two cases are considered: a lunar base with ⅙ gravity and a martian base with 0.38 gravity. Before a unit operation can be designed, the feed-stream composition, flow rate, and degrees of separation will need to be known. With this, a contacting method is chosen and the design made. Paramount in the design is the unit's cross-sectional area, which governs the throughput of materials, and the column height, which governs the degree of separation. These two factors determine the bulk equipment mass and volume. It is assumed here that feed-stream composition, flow rate, and degree of separation are known for the reduced-gravity setting. Then an Earth-based design is made using standard design techniques. The scaling rules presented here will then enable the Earth-based design to be modified for reduced gravity.

Bubble Columns

There are two general cases for scaling bubble columns: when the liquid is mixed solely from the rising action of the bubbles and when the liquid is mixed using an impeller driven by external shaft work.

When the mixing occurs from the rising action of the bubbles, a fine dispersion of bubbles provides a large interfacial area but poor mixing in the liquid. Conversely, large bubbles provide good mixing but lack surface area. Bubble size is optimized by using a correlation for $\kappa_L a$, where κ_L is the mass-transfer coefficient in the liquid and a is the interfacial area. The interfacial area is approximated by the area of a single bubble times the number of bubbles (for a monodisperse distribution). The number of bubbles for a fixed gas feed is inversely proportional to the bubble diameter cubed. This makes the interfacial area inversely proportional to bubble diameter. Optimization of $\kappa_L a$ is made from a correlation of experimental data using column height, bubble diameter, and gas flow rate (*Welty et al.,* 1976). Determining $\kappa_L a$ in reduced gravity is done by first optimizing the bubble column on Earth and then scaling for reduced gravity. Based on penetration theory, $\kappa_L \propto (V/d)^{1/2}$ for a rising bubble, where V is the rising velocity and d is the bubble diameter. The bubble velocity is found by equating buoyant force to drag force, and results in the scaling equation

$$\frac{V_L}{V_E} = \left(\frac{g_L}{g_E}\right)^{1/2}\left(\frac{d_L}{d_E}\right)^{1/2} \qquad (1)$$

where g is the acceleration due to gravity and the subscripts E and L are for the Earth and the low-gravity setting. The interfacial area, $a \propto 1/d$, used with equation (1) results in the scaling ratio

$$\frac{\kappa_L a|_L}{\kappa_L a|_E} = \left(\frac{d_E}{d_L}\right)^{3/4}\left(\frac{g_L}{g_E}\right)^{1/4} \qquad (2)$$

The details of deriving equations (1) and (2) are given in *Pettit* (1985). To determine the mass-transfer rate for low gravity, first the gas flow rate and Earth tower height are used in the correlation in *Welty et al.* (1976) to optimize $\kappa_L a/_E$ and determine Earth bubble diameter. Equation (2) then determines $\kappa_L a/_L$, which is needed to find the mass transfer rate in low gravity. If bubble diameter is made constant between Earth and low gravity by altering the bubble generator (sparger head), then $\kappa_L a$ is 0.64 and 0.79 times that on Earth for a lunar and martian setting. This decrease in $\kappa_L a$ is due to slower bubble velocity decreasing turbulent mixing.

The amount of mass transferred for a chemical species is $n_i \propto t\kappa_L a$ where n_i is the transferred mass of species i and t is the contact time. Using equation (2) gives the scaling ratio

$$\frac{n_i|_L}{n_i|_E} = \left(\frac{g_L}{g_E}\right)^{1/4}\left(\frac{d_E}{d_L}\right)^{3/4}\frac{t_L}{t_E} \qquad (3)$$

The mass transferred (species separation) is a given design criterion and remains the same between Earth and low gravity. The contact time then scales as

$$\frac{t_L}{t_E} = \left(\frac{g_E}{g_L}\right)^{1/4}\left(\frac{d_L}{d_E}\right)^{3/4} \qquad (4)$$

which for the same size bubble, requires a contact time 1.6 and 1.3 times that on Earth for a lunar and martian setting. A longer

contact time is needed to achieve the same mass transfer because of the reduction in $\kappa_L a$.

The column height is scaled knowing $h \propto Vt$ and by using equation (1) and (4), giving

$$\frac{h_L}{h_E} = \left(\frac{g_L}{g_E}\right)^{1/4} \left(\frac{d_L}{d_E}\right)^{7/4} \quad (5)$$

where h is the column height. For constant bubble diameter, the column height is 0.64 and 0.79 times that on Earth for a lunar and martian setting. Even though the corresponding values of $\kappa_L a$ are lower and the required contact times are greater, the slower bubble velocity more than compensates, giving an overall column height lower than one on Earth.

Column area, A, is proportional to $1/V$ because the bubble velocity is the rate-limiting constraint on the gas flow rate (*Pettit*, 1985). If the area is insufficient, excessive foaming will result and a large volume expansion will likely cause the column to overflow. The scaling ratio for area is

$$\frac{A_L}{A_E} = \left(\frac{g_E}{g_L}\right)^{1/2} \left(\frac{d_E}{d_L}\right)^{1/2} \quad (6)$$

where A is the column cross-sectional area. For constant bubble diameter, the column area is 2.4 and 1.6 times that on Earth for a lunar and martian setting. The larger area is needed to accommodate the reduction in bubble velocity.

The bubbles are introduced into the liquid with a sparger, a distributing manifold that contains many small holes from which the bubbles emerge. Small separate bubbles as opposed to semicontinuous bubble chains are desired. Under this flow regime, viscous forces dominate bubble formation at the sparger hole. Using dimensional analysis, the scaling ratio for sparger hole diameter is

$$\frac{Mg}{\sigma D}\Big|_E = \frac{Mg}{\sigma D}\Big|_L \quad (7)$$

where M is the bubble mass (which specifies bubble diameter), σ is the gas-liquid surface tension, and D is the hole diameter in the sparger. Once the bubble diameter and sparger hole size have been determined for the Earth design, equation (7) is used to specify the sparger hole size in the low gravity.

A small change in bubble diameter can have a significant effect on the mass transfer. Sparger bubble diameter is actually a distribution of diameters and only approximated by a single diameter in Earth-based design. Designing a sparger for low gravity based on the scaling of equation (7) is approximate at best. The actual bubble diameter may be far enough from the anticipated size to significantly alter the designed mass transfer rate. Only when actual experience is gained in low-gravity mass transfer will this effect be known, and until then, scaling by equation (7) will have to suffice.

When external mixing with an impeller is used, the rising action of the bubbles is not needed to supply the turbulence for efficient mass transfer so the bubbles can be made as small as practical to increase the interfacial area. If the bubbles are too small though, excessive foaming tends to occur and requires a large dead space for volume expansion. The power required to give adequate mixing in the liquid is 1 to 2 W/l (0.5 to 1 hp/100 gal) based on Earth experience. This power level is dominated by viscous dissipation and is not anticipated to significantly change in reduced gravity.

The bubble residence time is complex in a mixed bubble column and is not simply described by a rising velocity over the liquid depth in the column. The turbulence is strong and momentarily overpowers the buoyant forces, causing the bubbles to circulate around and around inside the vessel. When a turbulent eddy brings a collection of bubbles close to the surface, some of them will escape while others will recirculate. Gravity-driven buoyant force is still ultimately responsible for the separation, and for a given level of turbulence and column height, the bubble residence-time distribution remains inversely proportional to bubble rising velocity. In scaling a mixed bubble column for reduced gravity, the effects of gravity on the intensity and eddy size of the liquid-phase turbulence will need to be known to determine κ_L. Since liquid-phase turbulence has small density variations (the liquid being nearly incompressible), the gravitation effects are assumed to be small. If the impeller design and power levels remain constant between Earth and low gravity, the turbulent intensity and eddy sizes should also remain constant. In a mixed bubble column, then, the bubble contact time should keep its inverse proportionality to bubble rising velocity and the mass transfer coefficient should remain a function of the mixing.

In the absence of data on gravity effects of mixing, it would be safest to maintain the same impeller design and power levels used on Earth; thus κ_L is assumed to remain unchanged. Earth-based correlations, then, will specify κ_L. The interfacial area, again for a given gas flow divided among equally sized bubbles is $a \propto 1/d$. The mass transferred is $n_i \propto t\kappa_L a$. The contact time, while complex in a mixed bubble column, is assumed to scale as $t \propto 1/V$ when mixing intensity and column height remain constant. Equation (1) for bubble velocity is used to scale the mass transferred as

$$\frac{n_i|_L}{n_i|_E} = \left(\frac{g_E}{g_L}\right)^{1/2} \left(\frac{d_E}{d_L}\right)^{3/2} \quad (8)$$

Again, the mass transferred is a given design criterion so equation (8) places the following constraint on the bubble diameter

$$\frac{d_L}{d_E} = \left(\frac{g_E}{g_L}\right)^{1/3} \quad (9)$$

The present unknowns associated with gravity effects on turbulence require the scaling for mixed bubble columns to keep the impeller design, power level, and column height constant. This, coupled with the given criteria for gas and liquid flow rates and desired mass transfer, places a unique constraint on the bubble diameter as specified by equation (9). Bubble diameter is 1.8 and 1.4 times larger for mixed bubble columns on the Moon and Mars respectively. The column cross-sectional area is given by equation (6) and is 1.8 and 1.4 times larger respectively on the Moon and Mars. Sparger hole diameter is given by equation (7) and, for generating the larger bubbles, surprisingly gives the same hole diameter as on Earth for use on both the Moon and Mars.

Foaming may prove to be an onerous problem in low gravity. Increasing the bubble size may alleviate part of the problem, but systems that tend to foam badly on Earth may require a centrifugal foam breaker in low gravity. The extent of foaming and turbulence will really not be known until low-gravity experience is obtained.

Spray Towers

Dispersions of liquid droplets in a gas for spray-tower design can be scaled for low gravity. The gas and liquid flow rates and degree of chemical species separation are given conditions in the low-gravity environment. These conditions are used to design an Earth-based spray tower where droplet diameter, tower cross-sectional area, and tower height are determined. Scaling relations can then be used to determine the corresponding low-gravity condition. Similar caveats for bubble-tower scaling apply to spray-tower scaling. In the absence of experimental data in low gravity, the scaling rules give a first-order design. Variation in droplet diameter affects interfacial surface area, the mass transfer coeffients, and the contact time, hence the overall operation of the device.

As with bubble towers, interfacial area between low gravity and Earth is $a \propto 1/d$, where d now represent the droplet diameter. The droplet diameter is chosen by the hole diameter in the sprayer nozzle and is scaled according to equation (7). The simplest scaling procedure, although not the only choice, is to maintain the same droplet diameter between low gravity and Earth, which ensures the same interfacial surface area between the two environments. The droplet free-fall velocity is given by a force balance between gravity and drag and gives the same scaling equation as for bubbles in equation (1). A droplet will fall with 0.41 and 0.62 times the velocity on Earth for a lunar and martian setting.

The mass transfer coefficient for the gas phase surrounding the droplets, κ_c, is scaled from its dependence on V and d developed from experimental correlations between a single sphere and surrounding gas. From *Welty et al.* (1976), the correlation shows $\kappa_c \propto (V/d)^{1/2}$, which is not surprising since the same proportionality applies to κ_L for a bubble based on penetration theory as in bubble columns. This yields the scaling ratio

$$\frac{\kappa_c|_L}{\kappa_c|_E} = \left(\frac{g_L}{g_E}\right)^{1/4}\left(\frac{d_E}{d_L}\right)^{1/4} \tag{10}$$

which gives a mass transfer coefficient 0.64 and 0.79 times that of Earth's when on the Moon and Mars. The lower mass transfer coefficient is the result of a slower free-fall velocity.

The mass transfer for a chemical species is given by $n_i \propto tk_c a$, which is the same for bubble towers. Equations (3) and (4) then will apply to spray towers for scaling contact time.

The tower height is determined from the contact time and the droplet velocity relative to the tower. The gas phase moves upward against the motion of the falling drops, making $h \propto (V-V_g)t$, where h is the tower height and V_g is the gas velocity. The gas velocity is usually some fraction of the droplet velocity, $V_g = cV$, where c ranges from 0.2 to 0.5, which minimizes elutriation of the droplets from entrainment in the gas stream. Using the droplet velocity and contact time of equations (1) and (4) gives scaling for tower height the same as equation (5) for bubble columns. Even though the upward gas velocity is significant in spray towers, its effect cancels out when forming the scaling ratio because of its proportionality to droplet velocity. For constant droplet diameter, the tower height is 0.64 and 0.79 times that on Earth for the Moon and Mars. Even though the corresponding mass transfer coefficient is lower and the required contact time is greater, the slower falling velocity more than compensates, giving an overall tower height significantly lower than a comparable tower on Earth.

The tower cross-sectional area A, is dictated by the gas velocity giving $A \propto 1/V_g \propto 1/cV$. This results in the scaling of tower area given by equation (6). For constant droplet diameter, the tower area is 2.4 and 1.6 times that on Earth for the Moon and Mars. The larger area is needed to reduce the gas velocity in proportion to the reduction in droplet velocity.

Packed Columns

Scaling procedures have previously been developed by *Pettit* (1986) for absorption, stripping, and distillation-column design in low gravity. The scaling packed cross-sectional area is

$$\frac{A_L}{A_E} = \left(\frac{g_E}{g_L}\right)^{1/2} \tag{11}$$

which is the same result as in bubble and spray towers for constant droplet diameter.

Packed column height is nearly independent of gravity. Column height is dictated by the degree of separation, thermodynamics, the fluid contacting pattern, and geometry. A ratio called the number of transfer units, $m/\kappa_m a$, where m is the flow rate of either the gas or liquid phase and κ_m is the mass transfer coefficient based on m, contains the parameters that are affected by gravity and are needed together with the thermodynamics to specify column height. Varying the level of gravity will certainly affect m, κ_m, and a. These parameters have an interdependence, and correlations of experimental data show that even though a change is made in one of these, the corresponding effects on the other two will cause their ratio to remain nearly constant. In scaling a column for cross-sectional area, the internal flow rates, mass transfer coefficients, and interfacial area will all be affected, but their ratio as the number of transfer units will remain nearly unchanged, hence so will column height.

SUMMARY

Unit operations for gas-liquid mass transfer are standard processes found in industrial-based society. Expansion into the reduced gravity environments found on the Moon and Mars will require similar operations to support the base activities. The standard gas-liquid mass transfer operations require gravitational forces to drive and to separate the fluid phases and have to be appropriately scaled for the reduction in gravity. There are three basic contacting methods for gases and liquids: dispersing the gas as bubbles in liquid in bubble columns; dispersing the liquid as droplets in gas in spray towers; and flowing the liquid and gas in opposite directions through a packed column. In design for reduced gravity on the Moon or Mars, flow rates and degrees of separation for the intended process are used to design the device for use on Earth, then the process is scaled for the reduced gravity setting. The scaling will give overall cross-sectional area and tower height along with some necessary internal design. This in turn will allow equipment volume and mass to be determined, which are needed for transportation arguments when the process is to be shipped from Earth. The scaling procedures shown here are only intended for first-order design in the absence of experimental data from reduced-gravity environments. The scaling rules might be validated experimentally in high-gravity environments produced by rotation on Earth. This would be the next best evaluation short of performing the experiments in reduced gravity.

Acknowledgments. This work was performed under the auspices of the U.S. Department of Energy.

EPILOGUE

Exchanging of Mass

Bubbles in liquid, and droplets in gas
Swirling together to see what will pass
The species will run a diffusional race
Over hill, through dale, and past interface
When liquid and vapor have finished their play
They depart one another, and go their own way

DP 4/88

REFERENCES

Duke M. B. and Keaton P. W., eds. (1986) *Manned Mars Missions,* vols. I and II. NASA M002.

Mendell W. W., ed. (1985) *Lunar Bases and Space Activities of the 21st Century.* Lunar and Planetary Institute, Houston. 865 pp.

Pettit D. R. (1985) Fractional distillation in a lunar environment. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 507-518. Lunar and Planetary Institute, Houston.

Pettit D. R. (1986) Performance of absorption and distillation columns in a lunar environment. *Chem. Engr. Commun., 46,* 111-122.

Welty J. R., Wicks C. E., and Wilson R. E. (1976) *Fundamentals of Momentum, Heat and Mass Transfer,* pp. 634-636, 554-660. Wiley, New York.

COMBUSTION OF GASEOUS FUELS UNDER REDUCED-GRAVITY CONDITIONS

M. Yousef Bahadori

Science Applications International Corporation
Thermal Sciences Division
21151 Western Avenue
Torrance CA 90501

Raymond B. Edelman

Rockwell International Corporation
Rocketdyne Division, WC-79
6633 Canoga Avenue
Canoga Park CA 91303

The need for an improved understanding of fires is becoming critically important with increased space travel and utilization. While the control of fires in low-gravity environments is not well understood, it is known that buoyancy significantly affects flame behavior and characteristics. The objective of this research is to gain a more fundamental understanding of fires, and to quantify flame behavior under reduced-gravity levels. Non-premixed flames of gaseous fuels are considered in this study because they are relatively simple and easy to control, yet embody mechanisms found in all types of combustion processes ranging from uncontrolled fires to practical combustion systems. This paper presents some recent results from microgravity studies of these flames. In addition, the potential usefulness of lunar- and martian-based laboratories is discussed in order to understand the characteristics and behavior of fires in reduced-gravity environments.

INTRODUCTION

The problem of fire safety has been of equal concern both on Earth and in space. The twenty-first century will begin a period of regular space travel, manned space stations, lunar and martian bases, and deep-space exploration. All these activities raise the question of fire prevention in space, and the use of low-gravity environments to further our knowledge of combustion on Earth.

Microgravity combustion research has been vigorously pursued in the last decade in relation to fire safety issues as well as the fundamental understanding of combustion phenomena. Combustion studies of solid, liquid, and gaseous fuels have been conducted in Earthbound facilities that provide short durations of microgravity. Promising results have so far been obtained to warrant the continuation of this branch of combustion science.

The objective of this research is to gain a more fundamental understanding of fires, and to quantify flame behavior under reduced-gravity levels. Non-premixed flames of gaseous fuels are being investigated because they are relatively simple and easy to control, yet embody mechanisms found in all types of combustion processes.

In the following sections we discuss (1) the general characteristics of laminar and turbulent diffusion (i.e., non-premixed) flames, (2) the available Earthbound facilities for conducting reduced-gravity combustion studies, (3) some new results obtained from laminar diffusion-flame studies in microgravity, and (4) the critical need for understanding low-gravity turbulent flames, all directed toward the goal of understanding the behavior of flames not only in space but on Earth as well.

LAMINAR AND TURBULENT DIFFUSION FLAMES

The term "diffusion flame" classifies those types of flames in which the fuel and oxidizer are not premixed, whether the reactants are in solid (e.g., coal combustion), liquid (e.g., droplet combustion), or gaseous form (e.g., cigarette lighter flame). Unlike "premixed" flames, as in internal combustion engines, the burning process in diffusion flames is governed by diffusion of the fuel gas and oxygen toward each other to form a thin flame sheet that separates the two reactants. The schematic diagram of a normal-gravity gas-jet diffusion flame burning in a quiescent oxidizing environment is shown in Fig. 1, where the different physicochemical phenomena governing the combustion process

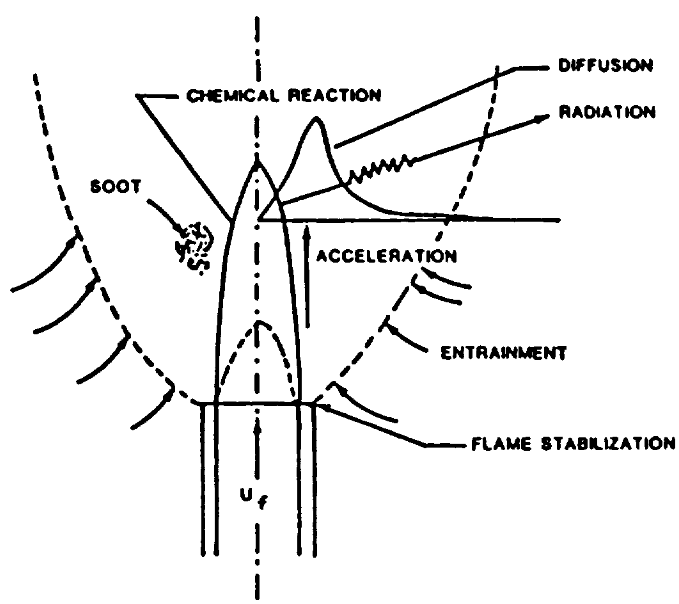


Fig. 1. Physical and chemical processes occurring in laminar gas-jet diffusion flames of hydrocarbons in normal-gravity environments.

are indicated. The gaseous fuel (e.g., methane) is injected through a nozzle, the tip of which acts as a flame holder.

In combustion processes, coupling exists between chemical kinetics, fluid dynamics, diffusion of species, inertia, radiation, and soot formation and disposition. In addition, under non-zero-gravity, buoyancy is imposed on these processes (due to the density difference between the hot combustion products and the cold environment). The buoyant force causes the hot products to be removed from the flame in the direction opposite to the direction of the gravitational force. This complicates the understanding of the coupled processes involved in combustion.

In zero-gravity environments, the buoyant force is eliminated, and the remaining processes become more tractable. Isolation, or even reduction of buoyancy, makes it easier to understand the interplay between these chemical and physical processes, which are not separable regardless of the gravity level. These phenomena are responsible for the very different behavior of flames observed in microgravity compared to those in normal gravity (*Edelman and Bahadori,* 1986).

Gas-jet diffusion flames are selected in this study because they are representative of a wide variety of combustion processes from the fundamental standpoint. These flames are laminar or turbulent, depending on the combination of jet momentum, nozzle diameter, and fuel properties. The classical behavior of a gas-jet diffusion flame in normal gravity (*Hottel and Hawthorne,* 1949) is shown in Fig. 2, which plots the dependence of length and structure of the flame on fuel velocity for a tube of given size. As the jet velocity increases, the flame transists from laminar (where mixing is governed by molecular diffusion) to fully developed turbulent behavior (where mixing is largely due to eddy diffusion or convection, with the final homogeneity being attained by molecular diffusion). It is this type of behavior that is anticipated to be strongly affected by the reduction in gravity level, as discussed later.

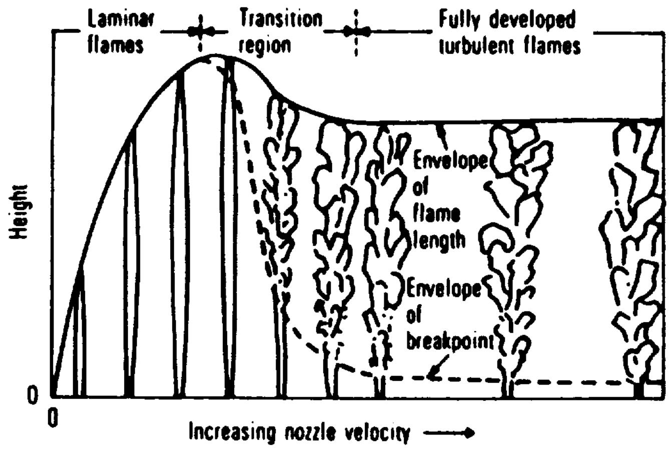


Fig. 2. Change in the flame height and behavior with increase in nozzle velocity for a typical gas-jet diffusion flame. From *Hottel and Hawthorne* (1949).

LOW-GRAVITY EARTHBOUND AND ORBITER FACILITIES

Several Earthbound and space shuttle facilities provide low-gravity environments for combustion research (see *Lekan,* 1989). To date, most of the reduced-gravity combustion studies (including premixed flames, solid-surface combustion, laminar gas-jet diffusion flames, particle-cloud combustion, pool fires, and droplet combustion) have been conducted in the 2.2-sec drop tower (10^{-5} *g*), 5.18-sec zero-gravity facility (10^{-5} *g*), and model 25 Learjet (10^{-2} *g* for approximately 15 sec, attached payloads) of NASA Lewis Research Center. In addition, studies are being conducted in the KC-135 aircraft of NASA Johnson Space Center (10^{-2} *g*, approximately 20 sec for attached payloads; 10^{-3} *g* for free-floating payloads). For an overview of combustion studies in low-gravity environments, see *Sacksteder* (1991) and *NASA* (1989). The middeck and spacelab of the space shuttle (10^{-5} *g*) provide much longer test times and lower gravity levels, and also allow more detailed diagnostic measurements of flames.

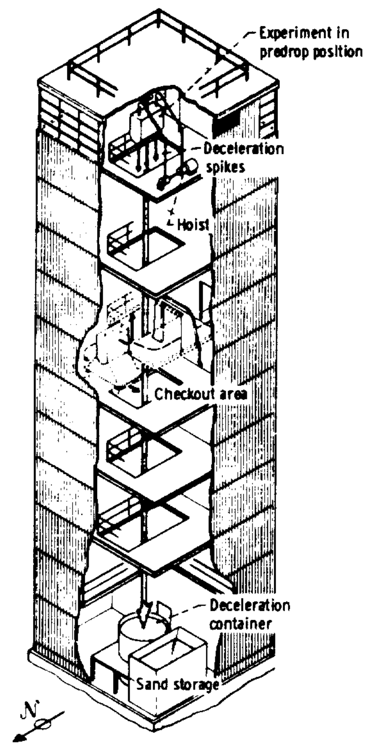


Fig. 3. 2.2-sec drop tower.

In the 2.2-sec drop tower (Fig. 3), the experiment package is enclosed in a drag shield that has a low drag coefficient. As the drag shield falls in this 27-m tower, the experiment package is released inside the shield. The air drag associated with the relative motion of the package within the shield is the only external force acting on the package. The shield comes to rest in a sand box at the bottom of the tower. The 5.18-sec zero-gravity facility, which provides a 132-m free-fall distance, is a 6.1-m-diameter, 145-m-deep steel-walled vacuum chamber at 0.01 torr. The sealed package is decelerated in a 6.1-m-deep container of polystyrene pellets. Aircraft flying parabolic (Keplerian) trajectories provide longer low-gravity test times, but at the cost of higher gravity levels. In the Learjet, the experiment is attached to the body of the aircraft. The KC-135 provides the same gravity level as in the Learjet for bolted-down experiments, but because of its size, also permits free-float packages. Intermediate acceleration levels,

especially lunar (1/6 *g*) and martian (1/3 *g*) gravities can also be achieved in the aircraft, providing opportunities to study combustion and fluid-physics phenomena under these specific reduced-gravity conditions.

MICROGRAVITY LAMINAR DIFFUSION FLAMES

Laminar diffusion flames of hydrogen and various hydrocarbons have been studied in the 2.2-sec drop tower (*Cochran and Masica,* 1970; *Cochran,* 1972; *Haggard and Cochran,* 1973; *Edelman et al.,* 1973; *Haggard,* 1981; *Babadori and Stocker,* 1989; *Babadori et al.,* 1990a,b; for a review of earlier work, see *Edelman and Babadori,* 1986) and the 5.18-sec zero-gravity facility of NASA Lewis Research Center (*Babadori et al.,* 1990c, 1991).

The normal-gravity flames of these fuels, when burned in quiescent oxidizing environments, generally flicker (due to hydrodynamic instabilities), are yellow (due to soot emission and burn-off), and are pencil-like in shape (due to the presence of buoyant force). In addition, the color of these flames is not strongly affected by changes in either pressure or oxygen concentration. This is a consequence of strong entrainment of oxidizer, again due to the effect of buoyancy (see Fig. 1).

Figure 4 shows a normal-gravity and the corresponding microgravity flame of propane. Compared to laminar flames in normal gravity, those observed in microgravity are flicker free, larger, diffuse, and rather globular. This is due to the absence of buoyant convection, leaving diffusion a much more dominant mechanism of transport. In addition, these flames are generally orange-reddish in color, which is a result of prolific sooting. Significant soot formation is caused by increased residence time, since the hot products of combustion accumulate in the vicinity of the flame due to the absence of buoyancy. As a result, continued combustion depends mainly on the diffusion of oxygen toward the flame front, causing major pyrolysis of the hot fuel-rich portion of the flame. As can be seen in Fig. 4, the microgravity flame appears to have a completely open tip. This suggests that extensive soot formation, radiative loss, cooler overall flame temperature, and a reduced oxygen supply contribute to extinction at the flame tip. It is quite possible that unburned and pyrolyzed hydrocarbons may escape through the flame tip in microgravity environments.

Pressure and oxygen concentration have a significant effect on flame characteristics, color, luminosity, and sooting behavior in microgravity compared to normal gravity (*Babadori and Stocker,* 1989; *Babadori et al.,* 1990b). Sooting was not visible in microgravity hydrocarbon flames at 18% oxygen in nitrogen, 0.5-atm environments, and the flames were entirely blue, whereas their normal-gravity counterparts were yellow, luminous, and very similar to flames under atmospheric conditions, or even high-pressure/high-oxygen-concentration flames. This has a very important implication; namely, there is reduced radiative heating and reduced hazard of flame spread to surrounding combustible materials in low-pressure/low-oxygen (compared to high-pressure and/or high-oxygen) microgravity flames. Figure 5 shows the effects of oxygen concentration on normal-gravity and microgravity flames.

High-pressure and high-oxygen-concentration environments also affect the intensity of burning in microgravity. Massive sooting, flame-tip opening, and extinction and soot breakthrough at the tip were observed even in 50%-oxygen environments. The tip-opening and soot-escape phenomena are unique characteristics of microgravity flames. Figure 6 shows the effects of pressure.

Recent tests (*Babadori et al.,* 1991) have shown that flame radiation is an order of magnitude higher in microgravity compared to normal gravity for laminar gas jet diffusion flames. Enhanced soot formation, larger flame size, and slow transport of the hot combustion products are the contributing factors. Figure 7 shows the flame radiance as a function of fuel volume flow rate

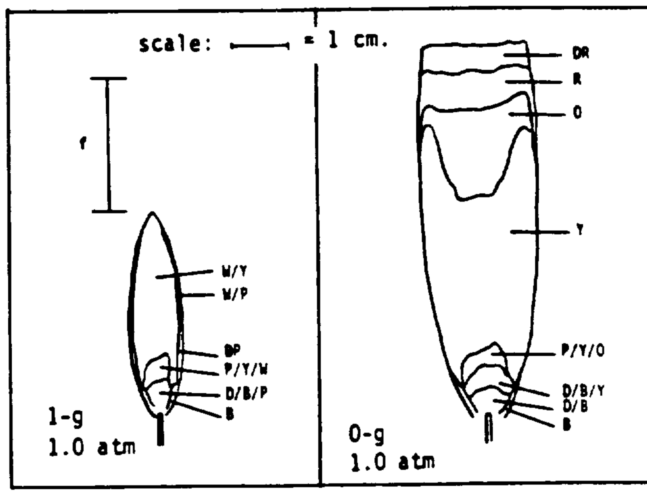


Fig. 4. Normal-gravity and microgravity flames of propane burning in quiescent air at 1 atm; nozzle radius = 0.0825 cm and fuel-flow rate = 1.0 cc/sec. The various colors observed are as follows: B (blue), BB (bright blue), D (dark), DB (dark blue), DP (dark pink), DR (dull red), O (orange), P (pink), R (red), W (white), and Y (yellow). The range of flicker (f) is also shown for the normal-gravity flames. From *Babadori et al.* (1990b).

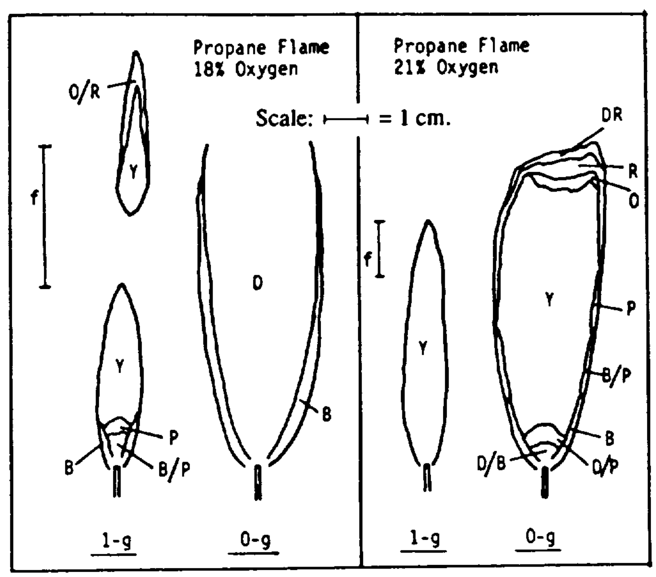


Fig. 5. Effects of oxygen concentration on normal-gravity and microgravity flames of propane at 1 atm; nozzle radius = 0.074 cm and fuel-flow rate = 0.96 cc/sec. The various colors indicated in the diagram are as follows: B (blue), D (dark), DR (dull red), O (orange), P (pink), R (red), W (white), and Y (yellow). The bars show the range of normal-gravity flame flicker (f). From *Babadori and Stocker* (1989).

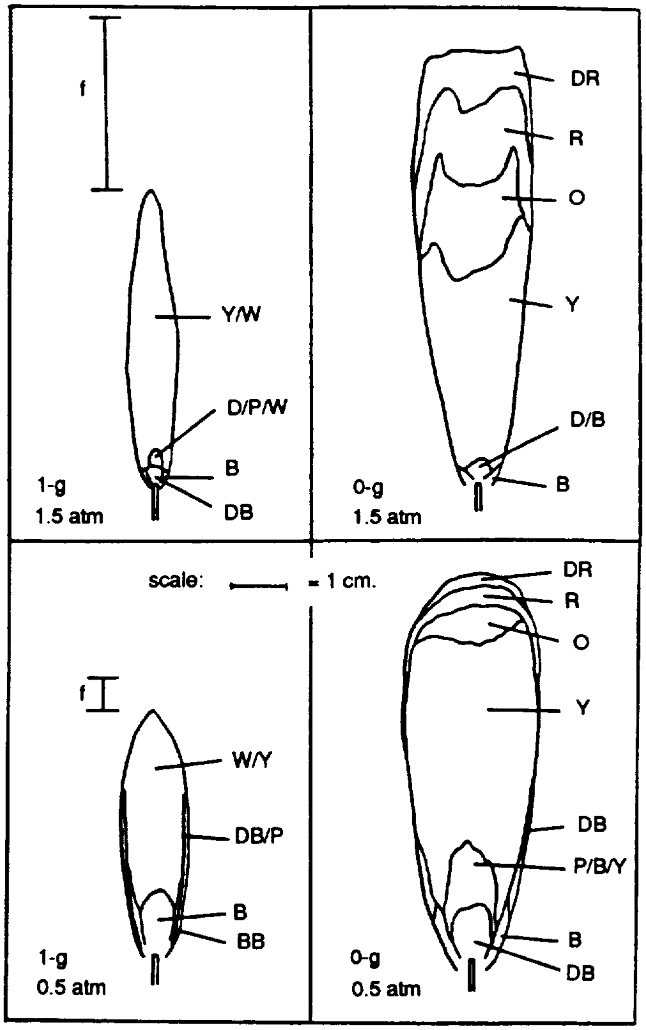


Fig. 6. Effects of pressure on normal-gravity and microgravity flames of propane burning in quiescent air (21% oxygen in nitrogen). For details, see Fig. 4. From *Babadori et al.* (1990b).

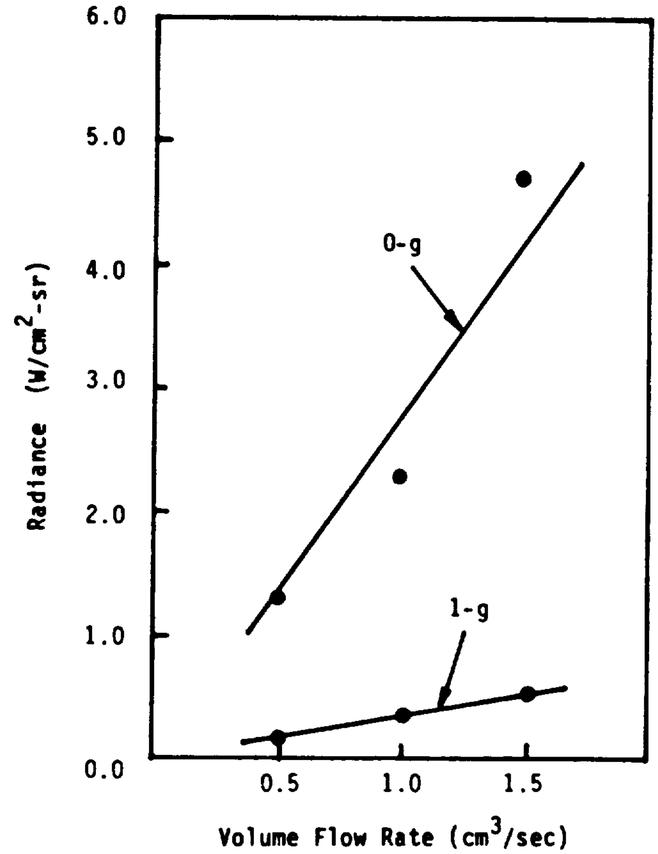


Fig. 7. Radiance as a function of fuel volume-flow rate for propane flames burning in air at 1.0 atm; nozzle radius = 0.0825 cm. From *Babadori et al.* (1991).

under both normal gravity and microgravity. The data suggest that compared to normal gravity conditions, radiative ignition of near-by materials may be promoted in low-gravity environments due to the increased radiative transfer.

A mathematical model has been developed (*Edelman et al.*, 1973) for the study of laminar diffusion flames under arbitrary gravitational accelerations based on the parabolic form of the equations of motion, which includes the effects of inertia, viscosity, multicomponent diffusion, and chemical reactions. Figure 8 shows the excellent agreement between the predicted and measured flame heights under both normal gravity and zero gravity. We have recently applied this model to a family of methane flames under different gravitational levels. Figure 9 shows the nondimensional centerline velocity vs. axial distance. Clearly, convective effects play a major and different role for different gravitational environments.

The full spectrum of observations on shape, color, luminosity, sooting, radiation, combustion products, and other characteristics of the flame are not understood. Experiments are required, along with appropriate diagnostics, under the gravity level of interest. Then, when combined with theoretical analyses, these results would provide a better understanding of fires on Earth and under reduced-gravity conditions such as those on the Moon, Mars, and in spacecraft environments.

TURBULENT DIFFUSION FLAMES

Turbulent gas-jet diffusion flames under normal gravity have been the subject of extensive theoretical and experimental studies for a number of decades. Figure 2 shows the classical behavior of a turbulent jet diffusion flame. As the jet velocity increases, the flame transists from laminar to fully developed turbulent behavior. For the tube size used in the flame study of Fig. 2, a velocity is reached where further increases in the jet velocity result in no change in flame height. This is a characteristic of momentum-dominated turbulent flames, i.e., flames in which buoyancy is not important.

Much progress has been made toward the characterization of momentum-dominated turbulent flames. However, this is not the case for low-momentum turbulent flames characteristic of un-

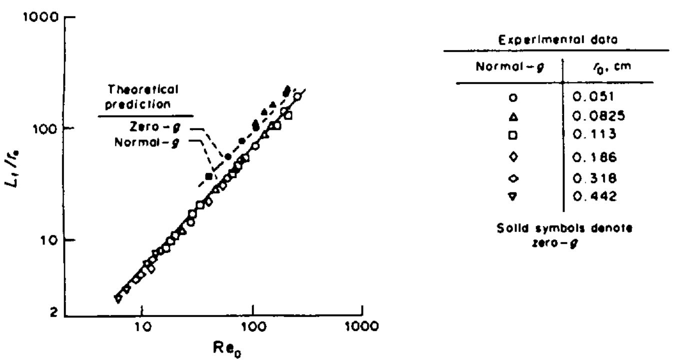


Fig. 8. Comparisons between the theoretical predictions (*Edelman et al.*, 1973) and experimental results (*Cochran and Masica*, 1970; *Cochran*, 1972) for nondimensional flame height (height/nozzle radius) vs. jet Reynolds number (jet velocity × nozzle radius/fuel kinematic viscosity); methane-air flames at 1.0 atm. From *Edelman et al.* (1973).

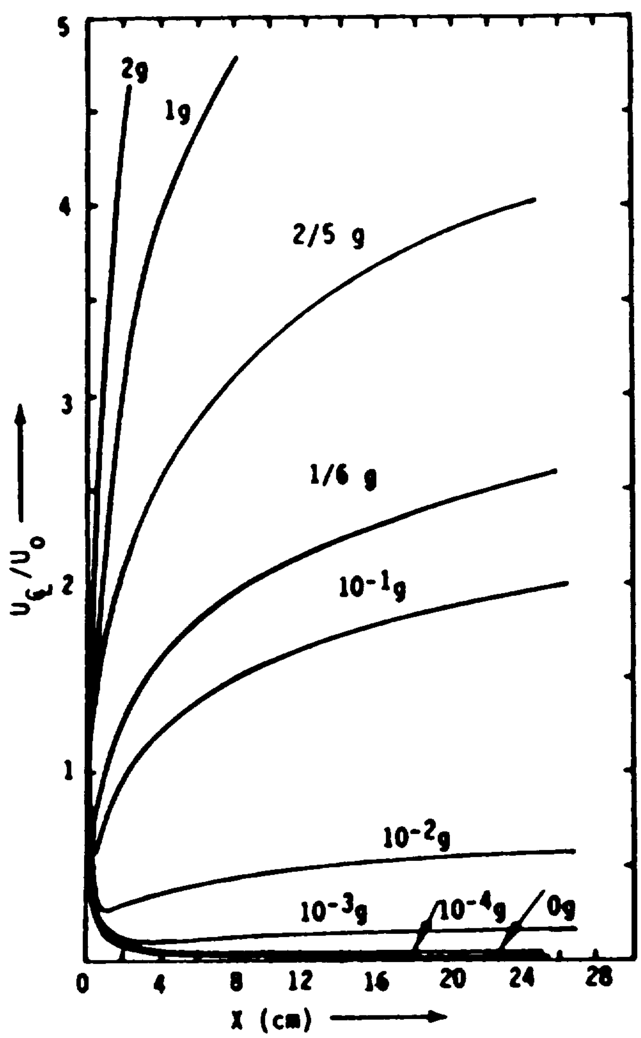


Fig. 9. Predicted nondimensional centerline velocity (with respect to jet exit velocity) vs. axial distance along the jet as a function of gravitational level; methane-air flames, nozzle radius = 0.0825 cm, fuel-flow rate = 1.0 cc/sec, pressure = 1.0 atm, and jet exit velocity = 46.8 cm/sec. From *Edelman and Babadori* (1986).

confined fires. In this case, the fire research community depends primarily on empirical results that, having been obtained under normal gravity, have the buoyancy effect inherently embedded within these correlations. When buoyancy is important (i.e., low-momentum flames, unlike Fig. 2), a constant height as a function of velocity is not reached in the turbulent region (see Fig. 10; *Wobl et al.*, 1949). The mechanisms responsible for this behavior are far from fully understood. Thus, the need for more fundamental data and analysis is apparent because of the requirement to define the hazard and control of fires not only on Earth but in space as well.

For low-momentum flames, strong interactions between buoyancy and turbulent-flame structure exist that affect the flame behavior and chemistry through two gravity-induced mechanisms. The first arises directly from the buoyant force acting on the time-averaged or mean flow field, and appears as a gravity term in the mean momentum equation. The second mechanism arises out of the interaction between density and velocity fluctuations, which appears as a source of turbulent kinetic energy. Under normal gravity, it is not possible to separate these two effects in terms of their impact on mixing rate, and hence, flame structure. Clearly, the advantage of operating in a low-gravity environment would be to provide a significant base of new information by isolating the combined effects of buoyancy.

CLOSURE

Although the effects of buoyancy on low-momentum flames have been qualitatively observed, it is only recently that quantitative descriptions of the phenomena affected by gravity have been attempted. Understanding this phenomena is not only of fundamental interest, but it is of critical importance to fire safety in space as well as on Earth. Furthermore, for processing and manufacturing in space, controlled flames are likely to be employed.

This paper has presented results that indicate significant effects of gravity on the flame structure. Moreover, it has been shown that to develop a more fundamental understanding of this phenomenon along with a reliable prediction capability, quantitative data obtained under reduced-gravity conditions uninhibited by test time and size limitations are needed. The potential to obtain data from experiments conducted on the Moon and Mars offers this opportunity, one that cannot be equaled in Earthbound facilities.

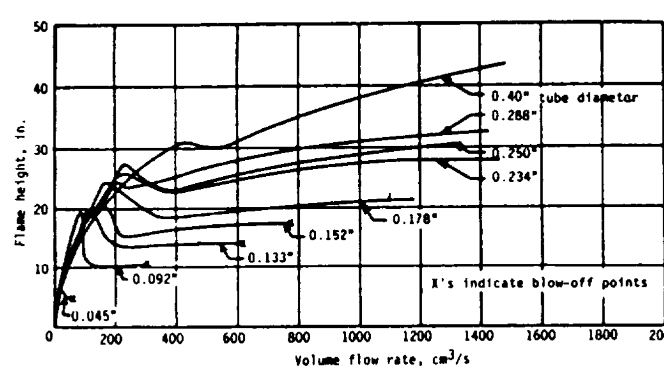


Fig. 10. Effects of fuel-volume flow rate and tube diameter on flame height for city gas diffusion flames. From *Wobl et al.* (1949).

Acknowledgments. This work is supported by NASA Lewis Research Center, under Contract NAS3-22822 with Science Applications International Corporation.

REFERENCES

Bahadori M. Y. and Stocker D. P. (1989) Oxygen-concentration effects on microgravity laminar methane and propane diffusion flames. Paper presented at the 1989 Fall Technical Meeting (Eastern Section) of The Combustion Institute, Albany, New York. The Combustion Institute, Pittsburgh. 4 pp.

Bahadori M. Y., Edelman R. B., Stocker D. P., and Olson S. L. (1990a) Ignition and behavior of laminar gas-jet diffusion flames in microgravity. *AIAA J., 28,* 236-244.

Bahadori M. Y., Stocker D. P., and Edelman R. B. (1990b) Effects of pressure on microgravity hydrocarbon diffusion flames. Paper AIAA-90-0651, AIAA 28th Aerospace Sciences Meeting, Reno, Nevada. American Institute of Aeronautics and Astronautics, New York. 6 pp.

Bahadori M. Y., Edelman R. B., Sotos R. G., and Stocker D. P. (1990c) Temperature measurements for microgravity laminar diffusion flames. Paper presented at the 1990 Fall Technical Meeting (Eastern Section) of The Combustion Institute, Orlando, Florida. The Combustion Institute, Pittsburgh. 4 pp.

Bahadori M. Y., Edelman R. B., Sotos R. G., and Stocker D. P. (1991) Radiation from gas-jet diffusion flames in microgravity environments. Paper AIAA-91-0719, AIAA 29th Aerospace Sciences Meeting, Reno, Nevada. American Institute of Aeronautics and Astronautics, New York. 4 pp.

Cochran T. H. (1972) *Experimental Investigation of Laminar Gas Jet Diffusion Flames in Zero Gravity.* NASA TN D-6523. NASA Lewis Research Center, Cleveland. 26 pp.

Cochran T. H. and Masica W. J. (1970) *Effects of Gravity on Laminar Gas Jet Diffusion Flames.* NASA TN D-5872. NASA Lewis Research Center, Cleveland. 25 pp.

Edelman R. B. and Bahadori M. Y. (1986) Effects of buoyancy on gas-jet diffusion flames: Experiment and theory. *Acta Astronautica, 13,* 681-688.

Edelman R. B., Fortune O. F., Weilerstein G., Cochran T. H., and Haggard J. B. (1973) An analytical and experimental investigation of gravity effects upon laminar gas jet diffusion flames. *Fourteenth Symposium (International) on Combustion,* pp. 399-412. The Combustion Institute, Pittsburgh.

Haggard J. B. (1981) *Forced and Natural Convection in Laminar Jet Diffusion Flames.* NASA TP-1841. NASA Lewis Research Center, Cleveland. 21 pp.

Haggard J. B. and Cochran T. H. (1973) *Hydrogen and Hydrocarbon Diffusion Flames in a Weightless Environment.* NASA TN D-7165. NASA Lewis Research Center, Cleveland. 28 pp.

Hottel H. C. and Hawthorne W. R. (1949) Diffusion in laminar flame jets. *Third Symposium on Combustion,* pp. 254-266. Williams and Wilkins, Baltimore.

Lekan J. (1989) *Microgravity Research in NASA Ground-Based Facilities.* NASA TM-101397. NASA Lewis Research Center, Cleveland. 16 pp.

NASA Lewis Research Center (1989) *Microgravity Combustion Science: A Program Overview.* NASA TM-101424. NASA Lewis Research Center, Cleveland. 18 pp.

Sacksteder K. R. (1991) The implications of experimentally controlled gravitational accelerations for combustion science. *Twenty-Third Symposium (International) on Combustion,* pp. 1589-1596. The Combustion Institute, Pittsburgh.

Wohl K., Gazley C., and Kapp N. (1949) Diffusion flames. *Third Symposium on Combustion,* pp. 288-300. Williams and Wilkins, Baltimore.

N93-14013

OCCUPATIONAL ERGONOMICS IN SPACE

J. Stramler

Lockheed Engineering and Sciences Company
2400 NASA Road 1
Houston TX 77058

INTRODUCTION

Ergonomics is often defined simply as the study of work. Related or synonymous terms include human factors, human engineering, engineering psychology, and others. The Human Factors Society is in the process of attempting to standardize some of these terms (*Christensen,* 1988).

Occupational ergonomics is a term that has been proposed to describe the study of the working environment and the human interaction with that environment, including the physical consequences resulting from having an improperly designed workplace. This field uses information from biomechanics, physiology, medicine, safety, and other fields. The primary goals of such work are to reduce or eliminate on-the-job hazards, reduce worker fatigue, and improve productivity. One of the beneficial side-effects of such work is that employee morale generally improves.

The failure to address and resolve problems associated with the Earthbound workplace commonly leads to such injuries as simple back pain, ruptured discs, a class of injuries referred to as cumulative or repetitive trauma disorders, crushed or severed limbs, and possibly even death.

The design of a typical workplace on Earth requires that a number of variables be taken into consideration. These can be divided into two major classes, human and environmental, as shown in Table 1.

The individual variables in each class may be further subdivided. For example, the human variable psychology may include such factors as stress and motivation. The environmental variable leverage may include friction, gravity, and handholds.

With so many variables involved, and the likelihood of interactions between them, the study of the working environment becomes a very complicated issue. However, since they can impact safety and health so significantly, consideration is imperative.

TABLE 1. Human and environmental variables typically involved in designing a safe, efficient Earthbound workplace.

Human Variables	Environmental Variables
Working posture	Pollution
Health status	Temperature/humidity
Fatigue level	Vibroacoustics
Training level	Tools required/provided
Protective clothing	Workstation/item positioning
Workload	Illumination
Individual differences	Leverage
Psychology	
Sociology	
Sex	

Humans have learned to work on the Earth over millenia. They have learned how to move about, what weights they can lift safely, and generally how to function in the 1-*g* environment. When humans begin to work in other environments, however, different rules may apply.

The routine space working environment presents some problems not found in the typical Earthbound workplace. These include radiation, intravehicular contamination/pollution, temperature extremes, impact with other objects, limited psychosocial relationships, sensory deprivation, and reduced gravity.

These are important workplace considerations, and may affect astronauts either directly at work or at some point during their life as a result of their work under these conditions. Some of the major issues associated with each of these hazards are presented in the remainder of this paper.

RADIATION

Radiation may take several forms. Probably the most dangerous in the short term is ionizing radiation. This is either particulate in nature or electromagnetic radiation composed of wavelengths much shorter than those of visible light. It may be in the form of primary radiation, as from cosmic rays and the sun, or secondary radiation from the interaction of primary radiation with the vehicle or its contents. Other types of radiation may exist from vehicular sources, such as nuclear reactors for power generation or instrumentation for crew health measures.

Ionizing radiation causes tissue damage at the cellular/molecular level. The effects range from slight illness to death in the short term, and cancer or death in the long term.

Nonionizing electromagnetic radiation is composed of wavelengths longer than those of visible light. This type of radiation is generated by power and communication systems, for example, and has been shown to have some biological effects as well (*Marha et al.,* 1971). Some commonly reported effects are abnormal offspring and cataracts. The pathology depends on the frequency and intensity of the radiation. The mechanisms for most of these effects are not yet fully known. The crew can be shielded from much of the radiation, but the tradeoff is the weight penalty the vehicle must carry.

INTRAVEHICULAR CONTAMINATION/ POLLUTION

Attempts have been made to limit the intravehicular contamination or pollution problem within spacecraft. Such pollution may consist of radiation (discussed above), chemical release or

outgassing, dust, noise, microbes, and particulate debris from crew activities.

Strict guidelines have been set up for flight qualifying items and the materials from which they are made before using them in the orbiter. Presumably, similar or even more stringent guidelines will be established for future vehicles to be used in long-duration spaceflights. The exposure of astronauts to chemicals for two or three years, as in a Mars flight, might result in some long-term disability problems.

The possibility of toxic chemicals or disease-causing organisms being in the spacecraft is a serious concern. Despite rigorous sterilization techniques, a bacterium apparently survived the preparation, launch, and over two years on the Moon in the Surveyor III camera (*Mitchell and Ellis,* 1971).

Humans can be a breeding ground for bacteria and viruses. Recycled waste (including air, water, and solids) are good candidates for carrying such contamination. Just as diseases are spread on Earth, they are likely to be spread in the vehicle. The problem may actually be worse in the vehicle due to the restricted volume. These conditions can present a very stressful environment for the crew.

VACUUM, REDUCED/ALTERED ATMOSPHERE

When engaged in extravehicular activity (EVA), astronauts must wear protective clothing to protect themselves from the vacuum in space or on the Moon and a reduced atmosphere as on Mars. Several models of spacesuits have been used over the years in the American space program. All of them, however, were pressure suits to provide a breathable atmosphere in a closed system.

The primary concerns in such work are the possible failure of the suit or having the suit punctured by a micrometeoroid. The consequences depend on the internal atmospheric makeup—whether it is pure oxygen or a mixed oxygen-nitrogen composition. If a mixed composition, the incidence of one or more forms of decompression sickness may result. In either case, death is certain unless rapid assistance is available.

TEMPERATURE EXTREMES

Temperatures can vary from about -200°F to about 250°F in the region of the Earth's orbital path about the sun. When exposed to the sun, reflective surfaces are employed to reduce heat absorption. When going to Mars, which is farther from the sun and colder, it may be desirable to reduce or even eliminate the reflectivity to help keep the astronaut warm. A spacesuit or specialized clothing with internal temperature regulation appropriate for the thermal environment is required to protect astronauts from this hazard.

IMPACT WITH OTHER OBJECTS

Objects of various sizes and from various sources exist in space. As more man-made debris accumulates in orbit around the Earth, the hazard to astronauts and vehicles in Earth orbit increases. As we venture through interplanetary space to Mars, the impact hazard should decrease. The degree of hazard might increase again slightly on approach to Mars, since that planet is nearer the Asteroid Belt and may have a larger number of uncharted small asteroids near its orbit than does the Earth.

Impact with any object of significant size could have disastrous consequences for a spacecraft and its crew. If the impact resulted in puncture of the vehicle pressurized volume, the crew could be exposed to a variety of hazards such as decompression sickness and flying debris. On a flight to Mars, even presuming repairs to and essentially full functional recovery of the vehicle were possible, the loss of air and other consumables could be critical if an inadequate supply remained to successfully complete the trip. There will be no resupply like there can be in Earth orbit.

The risk of such an event depends on the mission. In low Earth orbit, the larger debris particles are tracked. If the crew could be warned in time to make a course adjustment, the ship may avoid damage. Based on our experience with many vehicles having been sent into interplanetary space, the risk is probably quite low. However, previous vehicles have been relatively small craft, and the size of a manned vehicle to Mars will be much larger. One must presume that as the vehicle dimensions increase, the chances of impact also increase. Our ability to detect and avoid objects in interplanetary space is unknown.

For an astronaut working outside the vehicle, an outer garment was designed for spacesuits to provide some micrometeoroid protection. This outer garment is intended to stop the smaller objects and prevent them from penetrating the pressurized portion of the suit.

PSYCHOSOCIAL RELATIONS

The crew will form their own microsociety in space. There will be separation from loved ones, and from the Earth itself. The crew will be confined to the spacecraft or the base much of the time due to the hazards of working in the space environment. They will have to be a compatible group of people.

On a Mars flight, the crew won't even be able to see the detail of Earth for much of the trip. Thus communications with those back on Earth will be very important in maintaining morale, health, and productivity. Yet the communication will be hampered by long delays.

Crew selection and training will be very important issues in long flights. Some personality types will not be suited for such missions.

SENSORY DEPRIVATION

The problem of sensory deprivation or reduced sensory input in space is largely an unknown. During brief visits to the Moon, the problem with reduced stimulation of the vestibular senses under the lower gravitational pull may have been a determining factor in the astronaut's gait. Many of the astronauts developed a peculiar hopping gait for locomotion because it was deemed effective in maintaining their sense of equilibrium (*Graybiel,* 1974).

Other effects may only show up with extended stays. Humans' current sensors have developed during their evolution on Earth. An interesting question may be raised as to whether this sensory system will change in sensitivity or other ways over time in different environments.

In low Earth orbit (LEO), microgravity can be achieved by existing in a continual state of free-fall. But the gravitational field of Earth has not been reduced to any great degree. That will happen only when humans are a significant distance away. In interplanetary space, those gravitational accelerations besides the sun may be insignificant. Do humans have some sense that detects gravitational fields?

The Moon and Mars have no significant magnetic field. Some data exist that indicate that animals, given a choice, will escape

from or avoid a magnetically shielded environment. Would there be something aversive to working on the Moon or Mars under such conditions?

Many of our biological rhythms appear tied to sensory cues from cyclic activity related to Earth. Our circadian rhythms are tied to the length of the Earth day. The 24-hour cycle does not exist on the Moon nor apparently elsewhere in our solar system, although Mars has a rotational period close to that. Humans may have to artificially maintain certain rhythms to avoid "jet lag" types of problems.

REDUCED GRAVITY

The microgravity condition presents a number of problems to humans.

On short flights to LEO, consisting of a week or less in length, the primary concern is the space sickness or space adaptation syndrome that some astronauts experience. When it occurs, the symptoms can often be treated with drugs.

Due to lack of compression of the spine in microgravity, an increase in height occurs. This has necessitated use of a correction factor in sizing spacesuits so that the astronaut will be more comfortable working outside the spacecraft.

A cephalad fluid shift and overall fluid loss from the lower body occurs. Thus far, these appear to have no long-term health effects. These effects are countered by having crewmembers drink a lot of fluid prior to deorbiting.

On the longer-duration flights, certain physiological problems occur. These include a cardiovascular deconditioning, bone demineralization, and skeletal muscle tissue loss.

The cardiovascular deconditioning does not seem at this point to have any long-term effects on return to gravity, given that adequate provisions such as increased fluid intake are made for the return. Additional long-term studies should be done to verify this, however.

Until countermeasures were introduced, the Russian cosmonauts were taken off their return vehicles in stretchers after extended periods of microgravity. Apparently the orthostatic intolerance due to cardiovascular deconditioning in space was sufficiently severe that the returning cosmonauts could not stand on their own for a few days without feeling faint.

A major long-term concern about extended microgravity exposure is that of bone mineral loss. This phenomenon was first recognized in the Gemini flights, then confirmed with animals and humans in Russian flights (*Parin et al.,* 1975). The amount of reported bone loss in those early flights ranged up to about 15% in eight days. However, there is debate today about the accuracy of those data.

In later flights, including Skylab, better analytical techniques and an exercise countermeasures regimen were implemented. As a result, the reported bone losses were significantly reduced. The Russian flight data indicate variability among their cosmonauts, but with an average of about a 5% loss during a six-month flight (*Stupakov et al.,* 1984). Some preliminary information indicates that Yuri Romanenko, the Russian cosmonaut who spent 326 days in space, suffered only about a 5% bone loss.

In the only post-mortem study performed on cosmonauts, it was noted that the osteocyte lacunae were unusually large (*Nicogossian and Parker,* 1982), probably indicating bone loss.

Depending on one's definition, this bone loss may be similar to osteoporosis. One of the consequences of osteoporosis is that bones become brittle and more subject to fracture. Women are normally considered to be at greater risk for this disease, but recent evidence indicates that men are not immune. There appears to be a lag period of about 10 years for men (*Alvioli,* 1987).

Even if the astronauts return safely to Earth after a long-duration mission, there is some uncertainty about long-term occupational disability aspects. For example, the astronauts may experience premature fracturing later in life.

The skeletal muscles also suffer in microgravity. Since there is no need to retain a standing posture against gravity, the postural muscles of the leg and back are underused and atrophy. An initial report indicates that Yuri Romanenko lost 15% of the muscle volume from his legs (*Covault,* 1988).

Part of our lack of understanding in these areas is due to the techniques used in obtaining this type of information. Dual photon absorptiometry has been used recently as a better quantifier of bone mineral loss; a computerized tomography scan might provide better results, and for the whole body, not just one or two bones. The Jet Propulsion Laboratory (JPL) is currently working on a magnetic resonance imaging (MRI) device to quantify the amount of tissue loss (*NASA,* 1987). While this testing will expose the body to additional radiation, such research must be carried out to learn exactly what the effects of living in microgravity are.

Possible measures to counteract the bone mineral and skeletal muscle tissue losses include exercise that simulates working against the force of gravity, centrifugal force (usually referred to as artificial gravity), and what might be called "drug" use.

Exercise has been shown to reduce bone losses in the studies above. To do so, though, takes about two hours from each crewmember's day. This has a major negative impact on crew productivity.

Is an exercise countermeasures program alone adequate to prevent osteoporosis? What if an astronaut or cosmonaut sustains a fracture or becomes ill for a long period of time and is unable to exercise? Such a development could be a critical situation for that individual and a major setback for the mission. Without exercise, the crewmember would become subject to an even greater amount of bone demineralization. Should another mechanism be provided to assist in preventing bone loss?

The idea of a variable-gravity Earth orbital station has been proposed by the Sasakawa International Center for Space Architecture (*SICSA,* 1988). It was named the Variable Gravity Life Sciences Facility (VGLSF), and would be a rotating platform that provides centrifugal force of different magnitudes, depending on the distance from the center. A similar concept of rotating at least a portion of the vehicle has been discussed for reducing the bone mineral loss on long missions.

The use of drugs to prevent osteoporosis is a possibility, but most of them have undesirable side effects. Estrogen would obviously not be a good candidate for men. Other potential drugs might include calcitonin (*Alvioli,* 1987) or fluoride (*Posen,* 1985).

The important ergonomics and mission questions are, then, what effects will these bodily changes and the working environment have on astronauts' ability to carry out their assigned tasks in space or on the Moon or Mars? They could be fairly significant when all the variables are factored in.

Interpolation or extrapolation of human performance from current Earth-based data or may not be accurate in the exploration of other bodies. For example, a man who can lift 100 lb on Earth probably will not be able to lift 600 lb on the one-sixth gravity of the Moon, especially when encumbered by a 200-lb spacesuit.

One known extrapolation inaccuracy occurred when the astronauts arrived on the Moon. Preflight Earth-based simulator data had indicated they might walk with a much longer stride than was normal on Earth, and bound much higher. As indicated previously, many of the astronauts developed a completely different mode of locomotion—a gait resembling hopping or bounding.

An interesting result was noted from a preliminary analysis conducted by the author of some of human's potential capabilities on various solar system bodies that we might expect to visit within the next few decades.

Theoretically, Phobos's gravity and escape velocity would permit the first human-powered satellite launch from that moon of Mars. Whether this could be actually done or not will depend on the condition of the astronaut after a flight from Earth, spacesuit mobility, what kind of leverage an astronaut could achieve, the mass of the object, etc. Will this extrapolation prove to be valid?

In analyzing the work to be done in space or on the Moon or Mars, several classes of tasks can be stated now with reasonable certainty. Some of these have been summarized in *Hall* (1985), but many other types of tasks would have to be performed in constructing a Moon base, for example. Specific aspects of many of these tasks will have to await development of the actual hardware to be used.

What might happen to an individual's strength capabilities is important for working safely in space. Does a 15% loss in muscle mass correspond with a 15% decrease in strength? Considering both the bone and muscle loss, what decrease in safe working strength does it represent? The relationships aren't known yet.

The National Institute of Occupational Safety and Health (NIOSH) has produced a guideline for a specific type of lifting task on Earth (*NIOSH,* 1981). Similar guidelines could be developed for other types of tasks.

In this guideline, the authors define an action limit (AL) and a maximum permissible limit (MPL). The AL is the recommended weight limit for lifting under the given working conditions. This limit is designed to prevent injuries in the average healthy person. Lifting above the MPL incurs an unacceptable risk of injury.

Equations have been developed to permit calculation of AL and MPL values. These values are based on the initial and final positions of the object to be lifted, its mass, and the frequency with which the task is performed.

To generalize such guidelines to space, some additional variables have to be considered. These would include the gravitational field strength under which the work is being carried out, the clothing characteristics (i.e., a spacesuit or pressure suit), the conditions and time spent in microgravity prior to working on the task, and many of the other variables given in Table 1.

An orbiting laboratory similar to the VGLSF may be used to estimate human's capabilities under a range of gravitational accelerations and other conditions before going to the Moon or Mars. By proper positioning aboard such a vehicle, it could be used to simulate a variety of specific gravitational fields.

The restriction caused by the spacesuit is a major factor in working in space. The astronauts' reach and strength capabilities are greatly reduced and metabolic rates are increased.

We have begun to quantify the reduction in reach capability with the current shuttle spacesuit in NASA's Anthropometry and Biomechanics Laboratory (ABL) at the Johnson Space Center.

The percentage volume of one-handed reach capability in the suited condition is only about one-fourth to one-third that of the unsuited capability (*Stramler,* 1986). The two-handed reach capability, which simulates a task requiring two hands working closely together, has a much greater reduction. In the case of an approximately 50th percentile stature female subject, only about 3% of the unsuited reach volume was achieved.

Another study performed in the ABL was to determine the torque that spacesuited astronauts were able to produce in a simulated space station strut assembly task (R. Lewis, unpublished data, 1987). Under the conditions of the experiment, not unreasonable for actual construction in orbit, the maximum torque output was only about 11 ft-lb. This type of task, done repeatedly, especially in a spacesuit, is clearly a potential candidate for producing carpal tunnel syndrome, one of the repetitive/cumulative trauma disorders.

As shown in another study supported by the ABL, the metabolic cost or physical workload increases while working in a spacesuit (e.g., *Dierlam,* 1984).

Greater endurance can be achieved if the oxygen consumption for routine effort vs. maximal effort (the VO_2/VO_2max ratio) is kept as low as possible for a given task (*Kamon and Ayoub,* 1976). Under such conditions, the astronaut will require less rest, i.e., be more productive in a given time. Keeping this ratio low also tends to reduce the chances of injury (*Chaffin,* 1975).

One might be tempted to think that the reduced gravity in space or on other nearby bodies would tend to decrease injuries—that working in space is easier than in Earth's gravity. Work in space to this point has indicated that, given a proper set of restraints and mobility aids, it is much like work on Earth. This may not always be the case, however. In the case of long stays on the Moon or long-duration flights to Mars, for example, the greater physical effort required to manipulate the suit and at least some minimal amount of osteoporosis and muscular atrophy may actually increase the risk of injury.

Medical care will be limited in space. Medical facilities will probably resemble a small clinic or even battlefield conditions more than a hospital. Thus injuries should be prevented rather than treated.

It is also important to remember that when in space, the vehicle/base becomes the workplace, home, and recreational center all in one. Many accidents or injuries on Earth occur in the home or while playing. There is little reason at present, aside from the restricted habitable volume, to believe the situation would be any different in space.

There has been a great deal of talk about using robotics to complement humans in space, if not replace them. The use of robotics seems appropriate under certain conditions. However, what the activities involving manned exploration and working in space will allow in terms of robotics remains to be determined. Certainly the potential is there to provide relief from repetitive activities and those activities that may lead to human injury.

The only really definitive means of determining what humans can do on another body such as the Moon or Mars or in microgravity is to be there and conduct the tests. We have much to learn as we begin to explore these environments.

The goal of such work should be to establish some guidelines for use under those conditions and on other bodies in the solar system such as have been put forth by NIOSH for Earth-based work. Some initial guidelines might be the following: remain

below NIOSH AL equivalent; minimize VO_2/VO_2max ratio; minimize microgravity exposure duration; minimize radiation exposure; improve spacesuit mobility; reduce spacesuit mass; use the strongest people available; and use robotics when practical.

There will probably be several tradeoffs in following these guidelines. Some actually oppose others, given current technology. For example, the astronaut needs a spacesuit with high mobility and the lowest possible mass to work most productively. Yet to provide better shielding from radiation, more mass is required in the suit. What the tradeoffs will be are uncertain at this time.

Once humans have been to the Moon, Mars, and Phobos to perform some testing on their performance capabilities under these gravitational accelerations and other conditions, we should have the groundwork for predicting their working capabilities on any body in the universe that we might explore.

The fact that there are significant problems to be overcome shouldn't prevent humans from exploring other planets and ultimately the universe. We will find the means to overcome these problems. There were hardships in exploring the Earth, but we accepted them and conquered it. We will do the same in space.

REFERENCES

Alvioli L. V., ed. (1987) *The Osteoporotic Syndrome: Detection, Prevention, and Treatment,* 2nd edition. Grune & Stratton, Orlando.

Chaffin D. B. (1975) Ergonomics guide for the assessment of human static strength. *AIHA J.,* 505-511.

Christensen J. M. (1988) Human factors definitions. *Human Factors Society Bulletin, 231,* 8-9.

Covault C. (1988) Record Soviet manned space flight raises human endurance questions. *Aviat. Week Space Technol., 128,* 25.

Dierlam J. J. (1984) *Investigation of Mobility Differences Between Two Spacesuit Joint Systems by Metabolic Rate Measurements.* Technology Inc., Houston.

Graybiel A. (1974) Measurement of otolith function in man. In *Handbook of Sensory Physiology,* Vol. 6, Part 2 (A. J. Benson et al., eds.), pp. 233-266. Springer-Verlag, New York.

Hall S. B. (1985) *The Human Role in Space: Technology, Economics, and Optimization.* Noyes Publications, Park Ridge, New Jersey.

Kamon E. and Ayoub M. (1976) Ergonomics guides to assessment of physical work capacity. *AIHA Ergonomics Guide.*

Marha K., Musil J., and Tuha H. (1971) *Electromagnetic Fields and the Life Environment.* San Francisco Press, San Francisco.

Mitchell F. J. and Ellis W. L. (1971) Surveyor III—Bacterium isolated from lunar-retrieved TV camera. In *Proc. Lunar Sci. Conf. 2nd,* pp. 2721-2733.

NASA (1987) *Life Sciences Report,* p. 21.

Nicogossian A. E. and Parker J. F. (1982) *Space Physiology and Medicine.* NASA, Washington, DC. 208 pp.

NIOSH (National Institute for Occupational Safety and Health) (1981) *Work Practices Guide for Manual Lifting* (Tech. Rpt. 81-122). NIOSH, Cincinnati.

Parin V. V., Gazenko O. G., Yuganov Ye. M., Vasil'yev P. V., and Kas'yan I. I., eds. (1975) *Weightlessness (Medical and Biological Research).* NASA TT F-16, 105. NASA, Washington, DC.

Posen S., ed. (1985) *A Discussion of the Diagnosis and Treatment of Osteoporosis.* Huber Publishers, Toronto.

SICSA (Sasakawa International Center for Space Architecture) (1988) Variable gravity life science facility. *SICSA Outreach, 1.*

Stramler J. H. (1986) A comparison between space suited and unsuited reach envelopes. *Proc. Human Factors Society, 30,* 221-224.

Stupakov G. P., Kazeykin V. S., Kozlovskiy A. P., and Korolev V. V. (1984) Evaluation of changes in human axial skeletal bone structures during long-term spaceflights. *Space Biol. Aerosp. Med., 18,* 42-47. (Translation).

8 / *Enabling a Program for Human Exploration of Space*

THE REAL WORLD AND LUNAR BASE ACTIVATION SCENARIOS

Harrison H. Schmitt

P.O. Box 14338
Albuquerque NM 87191

A lunar base or a network of lunar bases may have highly desirable support functions in a national or international program to explore and settle Mars. In addition, Wittenberg et al. (1986), Kulcinski and Schmitt (1987), and Kulcinski et al. (1988) have reminded us that ^{3}He exported from the Moon could be the basis for providing much of the energy needs of humankind in the twenty-first century. Both technical and managerial issues must be addressed when considering the establishment of a lunar base that can serve the needs of human civilization in space. Many of the technical issues become evident in the consideration of hypothetical scenarios for the activation of a network of lunar bases. Specific and realistic assumptions must be made about the conduct of various types of activities in addition to the general assumptions given above. These activities include landings, crew consumables, power production, crew selection, risk management, habitation, science station placement, base planning, science, agriculture, resource evaluation, readaptation, plant activation and test, storage module landings, resource transport module landings, integrated operations, maintenance, Base II activation, and management. The development of scenarios for the activation of a lunar base or network of bases will require close attention to the "real world" of space operations. That world is defined by the natural environment, available technology, realistic objectives, and common sense.

INTRODUCTION

A lunar base or a network of lunar bases may have highly desirable support functions in a national or international program to explore and settle Mars. As yet, such bases probably cannot be shown to be absolutely necessary in such a program. However, the Moon's resources, its reduced gravity, and its proximity to the Earth as a proving ground for planetary settlement technology should not be ignored in the analysis and planning of such an endeavor. The Moon probably could serve as a means of reducing the complexity, the cost, and the risk of implementation of any long-term commitment to Mars.

In addition, *Wittenberg et al.* (1986), *Kulcinski and Schmitt* (1987), and *Kulcinski et al.* (1988) have reminded us that ^{3}He exported from the Moon could be the basis for providing much of the energy needs of humankind in the twenty-first century. Deuterium/helium-3 or "Astrofuel" (*University of Wisconsin,* 1988) fusion has numerous advantages over more conventional fusion and fission cycles, and may become the basis for providing large amounts of continuously available electrical power in space as well as on Earth. The by-products of Astrofuel production on the Moon also have the potential for making lunar bases into totally self-sufficient settlements.

Both technical and managerial issues must be addressed when considering the establishment of a lunar base that can serve the needs of human civilization in space. Many of the technical issues become evident in the consideration of hypothetical scenarios for the activation of a network of lunar bases.

The purpose of hypothetical timelines or scenarios is to begin that long and interesting process of bringing realism into the modeling of future mission requirements, in this case, the creation, operation, and maintenance of a network of productive bases on the Moon. It is a first step toward the development of a "Design Reference Mission" that can serve as the basis for developing engineering designs, consumables budgeting, launch support requirements, flight operations procedures, economic analyses, and management structures.

A detailed scenario delivered to NASA as part of a report by System Development Corporation (*Schmitt,* 1986a) portrays the major day-to-day activities related to the first two years in one scheme for the establishment, initial operation, and maintenance of a lunar base network. The explanations of the logic underlying this scenario were extracted and slightly revised for this paper.

The general assumptions underlying this particular scheme are as follows.

1. The principal functions and justifications for the lunar base network, aside from those related to nation building and international policy issues, are (a) the production of oxygen in the near term and ^{3}He in the long term for use in support of other space and Earth activities and (b) the continued scientific exploration and utilization of the Moon.

Lunar-produced materials for use in space have the basic advantage over terrestrially produced materials of lower export costs from a gravity environment only one-sixth that of the Earth. Further, ^{3}He or Astrofuel is a potentially very attractive fuel for fusion power that has a very limited availability on Earth but for which there is a large resource base on the Moon (*Kulcinski and Schmitt,* 1987). The production of Astrofuel on the Moon can give by-products to support self-sufficient lunar settlements.

Potential scientific activities on the Moon include support of lunar resource development, further extrapolation of the Moon's special planetological relationships to the Earth, Mars, Mercury, and Venus, and use of the unique advantages of the Moon's farside as a platform for astronomical observations.

2. The frequency of major spacecraft landings on the Moon in support of the activation of the first lunar bases will be one per lunar cycle. Although higher or lower landing frequencies, and thus frequencies of major launches from Earth or space stations,

can be accommodated, a frequency of one per lunar cycle appears to give a good balance between the following: (a) additional burdens on launch operations on Earth; (b) optimum sun angle for crew landings; (c) operational and safety implications of missing one scheduled landing with crews on the Moon; and (d) gradual escalation of long-duration exposure of humans to a reduced gravity environment. Landings on the Moon at a rate of one per lunar cycle also can support the activation of a second base provided that launch and spacecraft capabilities can support a step increase (possibly about 50%) in payload weight landed on the Moon per landing. The lunar landing frequency required to support the activation of a third base has not been examined, but it is likely that either a higher landing frequency or another major increase in payload weight landed per landing will be required unless it becomes possible to bootstrap additional bases from the first two.

3. Engineering designs for the major support systems for a lunar base network will be finalized prior to initiation of the activation of the first base. These support systems include landing modules (LMs), habitation modules (HMs), lunar roving vehicles (LRVs), power plants (PPs), regolith mining plants (RMs), oxygen prodution plants (OPs), Astrofuel production plants (APPs), agricultural plants (APs), storage modules (SMs), and resource transport modules (RTMs). On the other hand, it is likely that the operational testing of prototype equipment at the first base will disclose needed modifications. Thus, the original designs must include characteristics that will rapidly accommodate such modifications.

4. The site for the first base of the network will be selected as that which is best for the operational testing of all basic support systems as well as being suitable for resource production. The mineral ilmenite (Fe_2TiO_4) probably will be the raw material for oxygen production (*Williams and Erstfeld,* 1979). Ilmenite-rich regolith also appears to be most favorable for Astrofuel production (*Cameron,* 1988). It would be highly desirable to take advantage of our existing knowledge about ilmenite abundances related to an Apollo landing site. Solely from this perspective, either areas geologically related to the Apollo 11 Tranquillity Base or Apollo 17 Taurus-Littrow sites appear to be the best candidates for Base I because of the high abundances of ilmenite in their soils (*Taylor,* 1982). Science considerations would probably favor the Taurus-Littrow area, whereas the ease of operational access and total resources available would appear to favor areas north of Tranquillity Base.

5. The site for the second base will be selected as that which is best for sustained resource production if demand warrants. It may be that confidence gained from remote sensing of ilmenite-rich areas other than Taurus-Littrow and Tranquillity Base will permit selection of a Base II site that lies in the western region of the Moon. This would be very desirable from a scientific point of view, as would be a third base location on the lunar farside, such as in the large crater Tsiolkovskiy.

6. The lunar tour of duty for crews will be roughly 3 lunar cycles for the first year, 6 lunar cycles for the second year, and 12 lunar cycles for the third and subsequent years. Longer tours of duty or even permanent residence probably can be accommodated with a concurrent reduction in launch support requirements. However, it seems prudent to build up gradually from the Skylab, Salut, Mir, and space station experience with human adaptation and readaptation in reduced gravity environments.

7. The crew work cycle during base activation and operation normally will be 10-hour days and 6-day weeks. The Apollo experience indicates that this workload is easily sustainable in one-sixth gravity provided the long-standing problems in leg mobility and in the design and operation of pressure suit gloves are eliminated. At times, it may be difficult to resist longer hours and seven-day weeks if hardware permits.

Specific and realistic assumptions must be made about the conduct of various types of activities in addition to the general assumptions given above. Examples of such activities and the assumptions that might be made about them are given below.

Mission rules. Scenarios for the activation of a lunar base should include consideration of likely "mission rules," that is, ultimately nonnegotiable requirements related to crew safety. For example, the status of crew return modules would be checked prior to proceeding with a landing or a departure that might isolate a crew on the Moon if one of the return modules were inoperative. The establishment of mission rules is a continuously iterative process and may impact the overall scenario at any time.

Landings. The first landing at a base site (Day -28) is an automated or remotely guided placement of an HM keyed to a precisely determined and nonhazardous point on the surface and to the plan for the final architecture of the base. Twenty-eight days later (Day 0) the first crew lands manually, keyed to the previously landed HM and to the base plan. Sufficient reserves of propellants must be on hand for both initial landings to maximize the probability of success. Subsequently, both automated and crew landings can be made precisely to landing beacons on local sites selected or prepared by preceding crews. This will reduce the propellant reserves required for landing and consequently increase landed payload capability.

Crew consumables. The basic philosophy behind crew consumables supply is to have sufficient margins to maintain normal consumption if the next scheduled resupply mission did not take place. Mission rules and common sense will require that the crew begin to conserve consumables if a scheduled resupply were indeed missed. Consumables (water, food, oxygen, and nitrogen) that would eventually be produced at the base would ultimately begin to significatnly reduce landed consumables requirements.

Power production. Power production and storage for the base is obtained in two stages. First, relatively small power plants and power storage systems are included as modules with the landings of the habitation modules (Days -28 and 29). The first crew lands with a backup power module and power storage system (Day 0). These systems must provide power for both day and night operations and habitation. If solar cell and battery systems are used, it is likely that sun tracking solar arrays will be required so that excess power can be generated during the lunar day for battery charging. If fuel cells are used, or a combination of solar cells and fuel cells, then cryogenics for the fuel cells must be resupplied from Earth at least until oxygen and hydrogen are in production at the base. As in the case of crew consumables, it is planned to have margins for power consumables sufficient to maintain normal base operation through at least one missed resupply opportunity.

The second-stage power production and storage systems must be sized to provide the power necessary for continuous operation of the fully operational base. It would appear that both first- and second-stage power systems, even if they use nuclear heat sources, should include fuel cells. This would enable the base to efficiently use lunar oxygen and hydrogen for the production of water, with electricity as a by-product, and thus avoid dependence on the costly import of water.

Should fuel cells become a major component of base power systems and should their maintenance require replenishment of significant electrolytes containing Na, K, Cl, or F, the cost of resupply of these elements vs. the cost of lunar production should be examined. Lunar orange and green soils and KREEP basalts are potential sources of these elements (*Schmitt,* 1986b).

Crew selection. Crew selection and training leading up to full activation of a base will be governed largely by the specialized activities each crew will be required to perform. An appropriate payload specialist will be on each of the crews through full activiation, whereas subsequent crews responsible for base operation may be more generally trained. Once the upgraded landers are available for Base II activities, additional scientific specialists should be accommodated as permanent personnel at the bases. Habitation module designs should take into consideration this possibility of step increases in the numbers of base personnel.

Health maintenance considerations will make it highly desirable to have a trained physician as a payload specialist at each base at least by the time six persons are in continuous presence. Such physicians also will be required to fulfill a full range of other base responsibilities, as will the scientific payload specialists present throughout the base activation period.

Risk management. The activation of lunar bases will require some new attitudes as well as new approaches toward risk management. For example, once crews are continously active on the Moon, there cannot be a long-term stand-down in the use of the transportation system (as had been the situation with the space shuttle) on which base activities and, indeed, crew survival may depend. Confidence in the tranporation systems must be such that they can be used even in the face of an accident or unforeseen design deficiency. Further, a severely injured or ill person on the Moon must be treated there. Otherwise, the activation or operation of a base will be seriously compromised. Contingency plans should be aimed more toward quickly adding personnel to a base having a personnel problem rather than quickly returning a person or crew back to Earth.

Equipment design must include "fail-safe" philosopies as well as the capability to repair and upgrade rather than discard. Major external risks from the environment, such as solar flares, must be managed by initial habitation design and by easily implemented procedures should the crew be caught in an exposed situation during a flare. In this case, appropriate shielding materials and other design considerations should be incorporated into LRVs so that they can form the roof of an explosively excavated trench (*Dick et al.,* 1986).

Habitation. The delivery, check-out, inspection and maintenance, and upgrading of habitation modules are sequenced so that sufficient capability is available at all times and the lifetimes of modules are maximized. As the modules will need to be covered by 2-3 m of lunar soil for protection from solar flares and cosmic rays, it is anticipated that trenches will be excavated in the regolith next to the lander that delivered each module. In turn, this requires that the lander design both protect the modules from the effects of excavation and provide for off-loading and placement of the module in its trench. The LRV or other device must then have the capability to move nearby regolith over the module and cover it to the required depth.

The Apollo experience indicates that a "dust lock" (in contrast to an airlock) will be a mandatory component of the habitation module. Although the absence of lunar atmosphere prevents the billowing and air transportation of lunar dust outside the habitats, the crews will carry dust on their pressure suits through the entrances to the modules. The highly penetrating and highly abrasive character of this dust makes it a very undesirable addition to the module's interior environment.

Although the scenario provides for the upgrading of the habitation modules to accommodate continuous rather than discontinuous use (two lunar cycles on, one lunar cycle off), major upgrading may not be necessary depending on the initial design. However, it is likely that the joining together of new module components as a base develops will be desired as well as the addition of unanticipated new capabilities. Thus, the module design should include built-in interfaces for upgrades.

Science station placement. Each lunar base will certainly be a major scientific observatory for lunar, solar system, and astronomical phenomena. The base plan should therefore include an appropriately selected site for one or more scientific stations. The timeline provides for the deployment and activation (Day 10) and the regular inspection, maintenance, and upgrading of the base's scientific systems.

The location of sites that constitute the lunar base network will greatly affect the value of each site's scientific station. If the Mare Tranquillitatis were selected for Base I, then a western ilmenite-rich site for Base II and a farside southern hemisphere site for Base III would make good sense. Depending on the demand for lunar resources, Base III might well be a purely scientific site, particularly one that could take advantage of the unique astronomical "viewing" potential of the lunar farside.

Base planning. The layout and architecture of the core of each lunar base must be planned in detail prior to any landing or activation activity. The automated landing of the first HM and all subsequent landings should conform to these plans. The first crew must insure that the plan is not only feasible, but can conform to the realities of the selected site.

Some of the considerations for the planning process are as follows:

1. Proper location of all landers relative to the site of the resource production plants so that they can be used later either to store produced resources or their by-products or to be refueled and reused.
2. Proper location of the landers bringing RTMs so that the RTM launch area is appropriately spaced relative to the production plants and other facilities.
3. Proper location of the entire base relative to its resource base in order to maximize the efficiency of extraction, beneficiation, and transport of concentrates to the resource production plants.
4. Proper location of the scientific station and agricultural plant enclosure so that they are unaffected by base activities that create dust, gas, seismic noise, and high-velocity particles that could damage these facilities or adversely affect their performance.

Science. Subsequent to the initial scientific survey of the base area and prior to the activities leading up to full activation of resource production, general scientific activities dovetail well with the overlap of crews on three-lunar-cycle tours of duty. The activities contemplated are those that extend scientific knowledge of the Moon, deploy geophysical and astronomical sensors, and define potential resources accessible to the base.

Once there is preoccupation with the activities of resource production, extensive scientific investigation will require the landing of extra payload specialists or entire crews for this purpose. Such augmentation of the scientific activities at a base requires not only additional habitation capacity, but also more

frequent landings than assumed for this scenario or the provision for permanent residents. One other alternative that could increase time available for scientific activities is successful automation of other base operations once systems are activated. Time will tell whether this proves to be practical.

Agriculture. The initiation of the investigation of food production on the Moon and the later activation of an agricultural plant are related both to the need to minimize imports of food and to the need to dispose of biological waste through recycling. The agricultural experiments and facilities will probably include a large inflatable and pressurized greenhouse and may require a self-contained fuel cell power system to provide water and lunar night lighting for photosynthesis. Radiation sensitivity of some lunar crops may require regolith shielding on the greenhouses, combined with the use of light pipes during the lunar day. Ultimately, food produced on the Moon may become a significant commodity for export to space stations.

Resource evaluation. As resource production is one of the main functions of a lunar base network, the early and detailed delineation of ore grades is essential to the long-term operation of each production center. The evaluation of the distribution of ilmenite-rich and ilmenite-poor zones within the regolith, as well as the concentration of adsorbed solar wind gases, will be an ongoing process. Such evaluations will be essential to the development and implementation of a mine plan.

Although ilmenite probably is evenly distributed in individual ilmenite-rich basaltic lavas from which most local regolith is derived, it is also clear that ilmenite-poor zones will be present as a consequence of the deposition of layers of pyroclastic materials, avalanche debris, and impact debris fron nonlocal sources. Surface mapping, the interpretation of local geological features, and the grid-controlled analysis of bore hole samples will be required to adequately delineate the ilmenite-rich ore zones to be mined and the ilmenite-poor waste zones to be discarded or avoided.

It probably will be desirable to equip the LRVs with semi-automated or automated boring, sampling, and analysis systems in order to minimize the time required for resource evaluation.

The actual mining of the regolith will be conceptually similar to large-scale dredging operations such as used to mine rutile from placer deposits. The regolith mining plant (see *Sviatoslavsky and Jacobs,* 1988) will need to be mobile, with self-contained primary and secondary resource concentration systems and grade monitoring systems. This will minimize the quantity of bulk material transported to the production plants and provide the capability for close control of the ore grade being mined. The regolith mining plant must be capable of detecting and avoiding or removing obstacles to mining such as large boulders.

Readaptation. Although one-sixth gravity probably has significantly less adaptive effects on human physiology than does total weightlessness, it is likely that some activities related to a crew's eventual readaptation to Earth's gravity will be desirable. The protocol for these activities is initiated about two weeks before a crew's return to Earth. The protocol will probably include activities that gradually increase skeletal and cardiovascular stress over this period. By the time we begin to activate a lunar base network, space shuttle and space station research should have defined prophylactic measures against adaptive deterioration.

Plant activation and test. The activation and test of the power plant, the regolith mining plant, and the resource production plants are critical not only to future integration of base operations, but also to verifying designs. If design flaws are discovered during these activities, it is essential that overall designs permit correction of such flaws rapidly and at the base.

Storage module placement. With lengthened tours of duty and less frequent landings at Base I as Base II is initiated, it will be necessary to bring into service SMs that can not only provide for the landing and storage of consumables, but can deliver empty resource transport modules to the base. These SMs will probably require use of the step increase in landed payload capability that also will be needed as Base II is activated.

Resource transport module placement. The regular supply of oxygen, Astrofuel, and any other resources from the Moon implies the existence and regular delivery of empty RTMs to each production base once operational production is initiated. The scenario provides for these activities through the cycling of four and eventually five RTMs to and from each base. It appears that, with the assumptions made to develop this scenario, each base might launch a loaded RTM every two lunar cycles. With launches staggered, this means that a lunar oxygen, and perhaps fresh food, delivery to a space station can be made every 28 days with two operating production bases. However, because landings at each established base in a three-base network will occur at an average frequency of less than one every two lunar cycles, it will occasionally be necessary to return empty RTMs to the base in pairs.

Integrated operations. With the landing of the sixth crew and its planned six-month stay, the stage is set for a build-up to integrated operations. Initially, the sixth crew integrates regolith mining and resource production while the fifth crew integrates resource and by-product production with storage in old landers and/or RTMs.

In order to undertake the full integration of these systems as well as other necessary base functions, it probably will be necessary for the fifth and sixth crews to split into two-person shifts. It appears that this practice will be necessary indefinitely unless a high level of automation and systems reliability is possible or larger numbers of personnel are available.

Maintenance. Throughout the activation of a base, attention is given to inspection and maintenance of base facilities and plants. Once the base is in full and continuous operation, it is likely that one of the two-person shifts will be an inspection and maintenance shift. This shift will have to work its way through all base systems on a regular cycle. A capability for repair, replacement, and spares delivery must be clearly defined and implemented if base functions are to be maintained continuously. Further, inventory control of all discarded materials and parts should be maintained in case they might be of some unanticipated future use.

Base II activities. It is anticipated that the activation of a second base for resource production would follow the same general scheme as that for the first base except for the following modifications: (1) landings would be less frequent; (2) crew tours of duty would be longer and crew responsibilities more varied; and (3) landed payloads would be larger.

Management. Most of the technical and operational management of an operating lunar base network must be contained within the network itself. However, logistics coordination with space stations and Earth will be essential, first, to insure a successful activation of the network and, second, to properly phase exports, imports, and crew replacement. Thus, it would appear that, at least for the first few years, overall network

activities must be coordinated from Earth, but the individual bases must be capable of significant and ever-increasing operational autonomy.

CONCLUSION

The development of scenarios for the activation of a lunar base or network of bases will require close attention to the "real world" of space operations. That world is defined by the natural environment, available technology, realistic objectives, and common sense.

The natural environment must be understood, and Apollo and Earth orbital flights have given us much such understanding. Available technology is under our control, and it can be expanded to meet the objectives of the base. Realistic objectives come with vision, but they must be reevaluated and refined continually.

Finally, common sense in space comes with experience and the interplay of ideas. No one has a monopoly on common sense, but the synergistic interaction of many professionals will go a long way to providing all that is necessary. We have done it before. Let's do it again.

Acknowledgments. This paper was prepared as part of work for the Fusion Technology Institute and the Wisconsin Center for Space Automation and Robotics, University of Wisconsin, Madison WI 53706.

REFERENCES

Cameron E. (1988) Mining for helium—Site selection and evaluation (abstract). In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century,* p. 47. Lunar and Planetary Institute, Houston.

Dick R. D., Blacic J. D., and Pettit D. R. (1986) Use of chemical explosives for emergency solar flare shelter construction and other excavations on the martian surface. In *Manned Mars Missions Working Group Papers,* Vol. 1, pp. 478-493. NASA M002.

Kulcinski G. L. and Schmitt H. H. (1987) The Moon: An abundant source of clean and safe fusion fuel for the 21st century. *11th International Scientific Forum on Fueling the 21st Century.* Moscow, USSR.

Kulcinski G. L., Cameron E. N., Santarius J. F., Svatoslavsky I. N., and Wittenberg L. J. (1988) Fusion energy from the Moon for the 21st century (abstract). In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century,* p. 147. Lunar and Planetary Institute, Houston.

Schmitt H. H. (1986a) Lunar base network activation scenario. In *Final Report: Lunar Power Systems,* pp. 2-1 to 2-43. NASA-JSC Contract NAS9-17359.

Schmitt H. H. (1986b) Lunar materials. In *Final Report: Lunar Power Systems,* pp. 6-1 to 6-12. NASA-JSC Contract NAS9-17359.

Sviatoslavsky I. N. and Jacobs M. (1988) Mobile helium-3 mining system and its benefits toward lunar base self-sufficiency. *Space 88: Engineering, Construction, and Operations in Space,* in press.

Taylor S. R. (1982) *Planetary Science: A Lunar Perspective,* pp. 115-175. Lunar and Planetary Institute, Houston.

University of Wisconsin (1988) *Astrofuel for the 21st Century.* College of Engineering, University of Wisconsin, Madison.

Williams R. J. and Erstfeld T. E. (1979) *High Temperature Electrolyte Recovery of Oxygen from Gaseous Effluents from the Carbochlorination of Lunar Anorthite and the Hydrogenation of Ilmenite: A Theoretical Study.* NASA TM-58214. NASA, Washington, DC. 51 pp.

Wittenberg L. J., Santarius J. F., and Kulcinski G. L. (1986) Lunar source of He-3 for commercial fusion power. *Fusion Technol., 10,* 167-178.

MOON PARK: A RESEARCH AND EDUCATIONAL FACILITY

Kyoichi Kuriki

Institute of Space and Astronautical Science
Yoshinodai
Sagamihara-shi
Kanagawa 229
Japan

Takao Saito and Yukimasa Ogawa

Obayashi Corporation
Kanda Tsukasa-cho
Chiyoda-ku
Tokyo 101
Japan

Moon Park has been proposed as an International Space Year (ISY) event for international cooperative efforts. Moon Park will serve as a terrestrial demonstration of a prototype lunar base and provide research and educational opportunities. The kind of data that can be obtained in the Moon Park facilities is examined taking the minimum number of lunar base residents as an example.

INTRODUCTION

As announced by President Reagan in his State of the Union Address to Congress in January 1988, mankind is expected to return to the Moon around the year 2000. The purpose of the return to the Moon is lunar base construction for permanent residence, which is required for lunar industrialization. In order to show the feasibility of lunar base construction, a ground-based demonstration is considered the most feasible approach in validating the lunar base design.

At the Pacific International Space Year (ISY) Conference held in Hawaii in August 1987, the present authors proposed the Moon Park concept as an ISY event to be achieved under international collaboration. Although 1992 is the year proposed for either operation or starting construction, the facilities constituting Moon Park are designed to be permanently operational.

The main facility of Moon Park is the training center simulating an outpost on the Moon, which is combined with the Controlled Ecological Life Support System (CELSS) as depicted by the diagram in Fig. 1. The CELSS is not only for the life support of the training center but is also studied as a key technology. Crew activities are observed by behavioral scientists and are even open to the public, as long as they are not significantly disturbed or degraded by doing so. If an open demonstration is supplemented by lectures and exhibits in the museum, the involvement of young students will be greatly promoted.

Basic technological development in the training center puts emphasis on CELSS demonstration and on studies in human behavior and psychological factors in a confined space. These technologies, together with others listed in Fig. 2, contribute to the lunar base. The CELSS in Moon Park is not a fully closed system, but is provided with several functions: water purification and recycling, management of human waste products, and cleaning and recycling of atmospheric gases.

Taking into account oxygen production from lunar soil, the first two items are regarded as urgent issues and discussed in the present paper in some depth. The objective of the present paper is to define the roles of the training center with its simulation of the crew habitat so as to derive conclusions for the design guidelines of the lunar base.

The major objectives of the studies on the CELSS and the human factors in the training center are to find the design guidelines for the minimum required number of crew for the proposed task, and the minimum dimensions of working and living space required for this crew, in conjunction with the life support needs and psychological factors affecting a small, isolated task group working in a confined space. These criteria will be necessary to design a manned outpost for lunar and planetary exploration. The

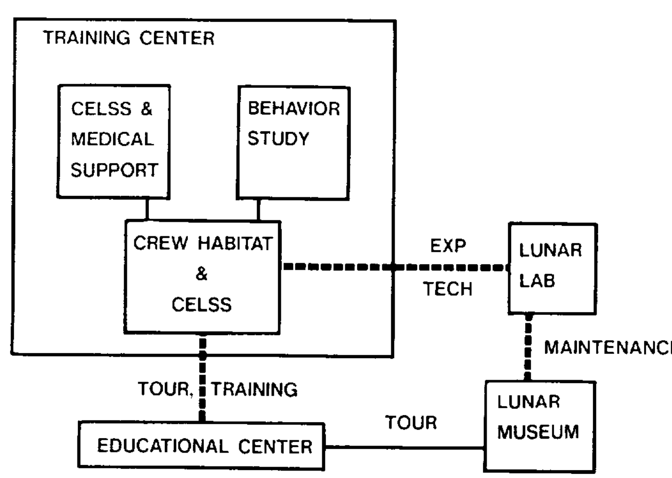


Fig. 1. Moon Park complex.

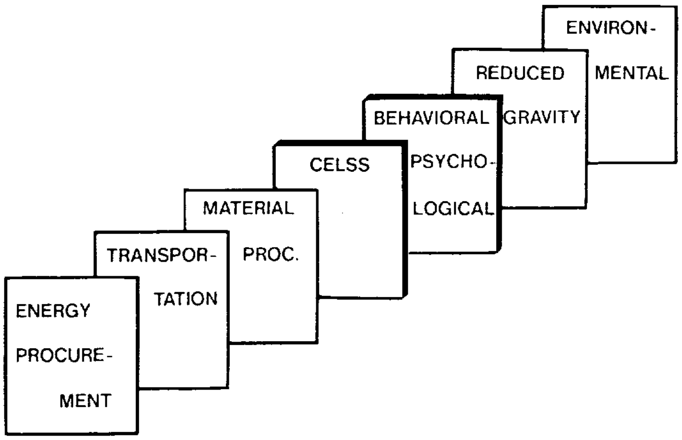


Fig. 2. The key issues of lunar industrialization.

present paper gives preliminary estimations for these values and points out influential factors that should be intensively studied in the Moon Park.

CONTROLLED ECOLOGICAL LIFE SUPPORT SYSTEM

The CELSS in the lunar base or Moon outpost will not be entirely closed but will be periodically replenished with protein food from Earth and provided with oxygen from the lunar factory. Vegetables, on the other hand, should be supplied from the hydroponic plant unit in the lunar base. The simulated CELSS of the training center in Moon Park is designed as shown in Fig. 3. The outside environment depicted in this diagram may correspond to the lunar regolith and landscape, and the oxygen factory outside the lunar base. Human waste and kitchen garbage are stored and processed in the biological reactor. The fertilizer generated in the reactor is transferred to the vegetable plant unit.

One of the problems related to the bioreactor is its conversion efficiency. If it is too low, vegetable supply will not satisfy the crew requirement and will have to be procured from outside. In this case, the secondary waste in the reactor will have to be managed somehow. The second problem is the speed of the reactor. If it is slow, the size of the reactor or reservoir will become large. Large size, however, is advantageous from the viewpoint of system stability, as will be discussed later.

The stability issue is most crucial in determining the crew size of the lunar base. Disturbance may arise from both quality and quantity of the waste and there is a maximum level of fluctuation that the reactor system can tolerate. Suppose such a threshold value for instability is 25% and the type of disturbance is disease, which should be a minor problem, or the absence of a crew, the minimum crew number is estimated to be four, which corresponds to the shoulder of the CELSS curve in Fig. 4. In the following, the technological bases for the characteristic values of the reactor are introduced.

WATER RECLAMATION AND WASTE MANAGEMENT

Due to lack of hydrogen on the Moon, water will be a precious material and its use must be optimized. An ordinary Japanese citizen uses about 250 l of water a day for the purposes listed in Table 1. The amount of cooking may be reduced to about one-third of terrestrial use by avoiding the boiling method of cooking and using the microwave oven. Water required for toilet flushing is related to the scheme employed for waste management. The water in a conventional toilet is not used as a processing agent, but as a carrier to a processing facility. The water required for this purpose, therefore, may be reduced by directly transporting the waste to the bioreactor as had been done in Japanese farming in the past. Taking these modifications into account, the lunar base water requirements will be reduced by two-thirds, as shown in Table 1.

In manned spacecraft to date, a physicochemical system has been employed as the most reliable method of water reclamation. In the lunar base, however, physicochemical systems are not suitable because of their increased water requirements; thus, we should apply the water generation system with microbes, as is widely used on Earth.

There are two kinds of microbial water treatment: aerobic and anaerobic. With limited resources of energy and oxygen on the Moon outpost, the anaerobic system is preferred. The anaerobic

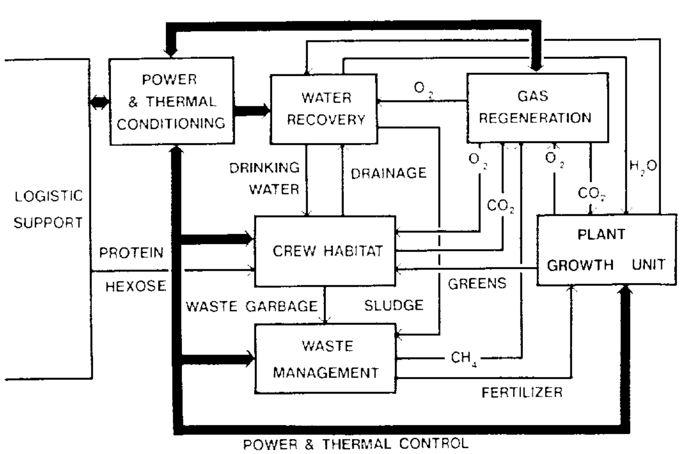


Fig. 3. Diagram of CELSS.

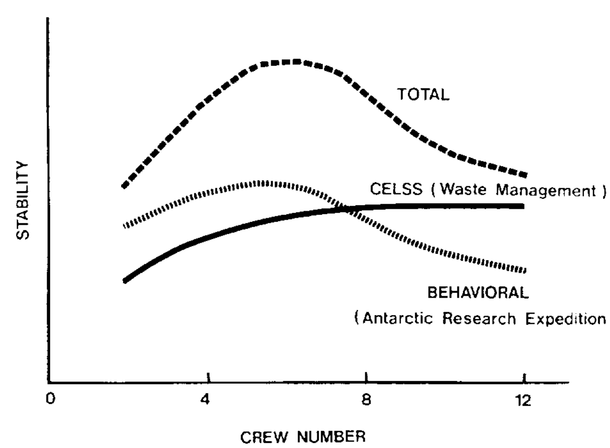


Fig. 4. Stability of closed ecosystem.

TABLE 1. Water consumption.

Purpose	Terrestrial (l/man/day)	Lunar Base (l/man/day)
Drinking	2	2
Shower	50	15
Cooking	50	15
Toilet flushing	50	15
Clothes washing	50	10
Cleaning (facility)	10	3
Others	38	33
Total	250	93

microbes, which are active in oxygen-free environments, decompose the organic waste in the used water, produce organic acids, and then convert them into methane and carbon dioxide. Because the extent of decomposition by the anaerobic system is limited, the assistance of an aerobic system is required for complete decomposition. In the further evolved lunar base where oxygen is available from a lunar factory, the aerobic system will be totally used, as it is more efficient and productive.

The water treated in the bioreactor is further processed physicochemically, as shown in Fig. 5, and is turned into drinking water. Methane, the by-product from the above system, is useful as an energy source, and the sludge is useful as fertilizer for the vegetable plant. The technologies of the water reclamation system discussed above have been terrestrially demonstrated in Tokyo in 1983 (*Ogawa,* 1985). A glass of water, about 100 ml, is obtained for a cost of less than one cent, only a few times as expensive as the city water in Tokyo.

The solid human waste will also be decomposed by the microbes in the compost tank. As discussed earlier, this may reduce the toilet water requirement. After releasing CH_4 and CO_2, the processed solid waste will be sterilized with UV radiation, completely sanitized, and eventually applied as fertilizer for the vegetable plant.

When the microbial system is applied to the lunar base, as demonstrated on Earth, two problems may arise. One is the applicability of lunar soil or crushed rock for the filter. However, no hazard was observed in a terrestrial experiment at NASA Johnson Space Center where a simulated lunar soil was applied as a medium for plant growth. The prospects of the use of lunar soil for a filter also seem hopeful. The other problem is the bubble handling at ⅙ *g* on the Moon. An artificial acceleration will be required for efficient operation of the liquid/gas system.

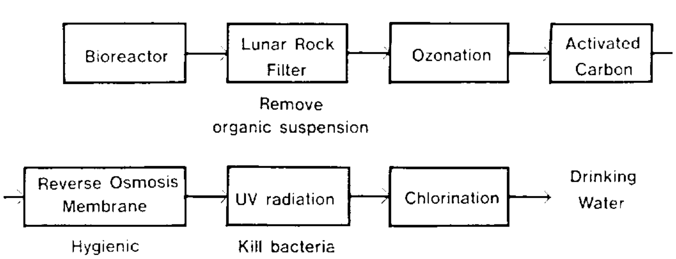


Fig. 5. Water regeneration process.

CREW BEHAVIOR AND ROLES

The minimum crew number for the Moon outpost is assessed from two factors. One is the stability of the crew's emotional behavior in confined habitat space. When the number of crew is extremely limited, fewer than four for example, the crew will find it hard to get along with one another. If the team size exceeds about 10, on the other hand, the crew will tend to lose frequent contact with each other. According to the summary report of the Japanese Antarctic Research Expedition, such loss of human communication will cause an unstable psychological state of the crew (*Nishibori,* 1958). This may result in a catastrophe for the team. An optimum number of crew members is suggested to be five or six so that they have frequent communication with each other and thereby make their community stable as described by the curve in Fig. 4. The bold dotted curve represents the product of the other two items.

The minimum number of crew is also discussed from the standpoint of the expertise required for lunar base operation. The type and miminum number of experts are listed in Table 2. The two electrical engineers are assumed to be specialists in power/electrical engineering and telemetry. One of the two mechanical engineers is an expert on CELSS, and the other is responsible for the O_2 generator. If a biological scientist supports the CELSS maintenance and a geologist supports the O_2 generator, the reliability of the lunar base community will be enhanced.

From the assessment given above, the most probable number of the Moon outpost crew is 8 to 10. An eight-person crew is assumed for the discussion in the next section.

TABLE 2. Crew composition.

Role	Number
Cook/Nutritionist	1
Medical Doctor	1
Mechanical Engineer (CELSS/O_2)	2
Electrical Engineer	2
Scientist (CELSS/O_2)	2
Total	8

BASE VOLUME REQUIREMENTS

Within the crew habitat with CELSS, the areas for water and gas treatments and waste management have to be taken into account. Based on the previous system design, about 120 m^3 is required as the volume of water and waste management facilities for eight people. If a compact O_2 generator is developed for production on the Moon, the CELSS operation with a bioreactor will be greatly improved. The volume required for the O_2 generator is assumed to be 100 m^3, including the storage tanks.

The design of the crew's private compartments is of prime concern, since the crew must maintain sound psychological conditions while being confined in a closed area for a prolonged amount of time. The habitat volume required, as shown in Fig. 6, depends on the length of stay. Assuming the residence time of a crew in the lunar base to be about a year, 25 m^3 per person is proposed for their personal compartment to allow considerable comfort. The dining room, which is to be used as a reading and meeting room as well, is essential. This should be 100 m^3 in volume. In addition, the kitchen requires 25 m^3, the workshop and

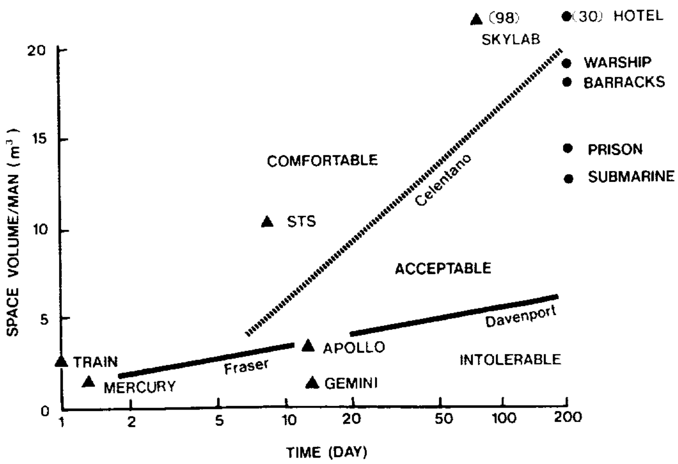


Fig. 6. Space volume for long-term habitation. Data from *Architectural Institute of Japan* (1980) and *Connors et al.* (1985).

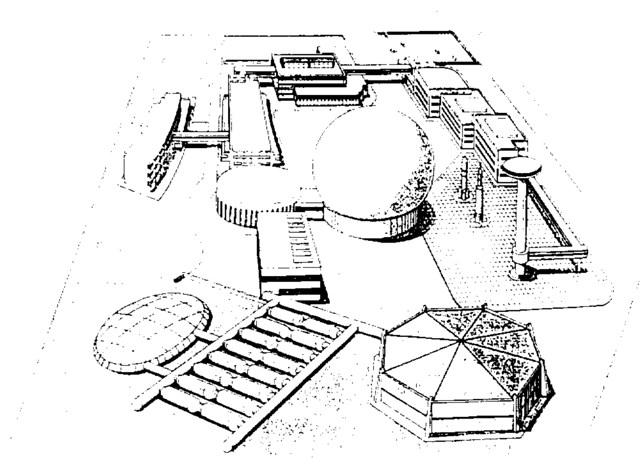


Fig. 7. Moon Park.

laboratories 350 m^3, and the utility space 250 m^3. These requirements, along with 360 m^3 for miscellaneous purposes, constitute the total volume of the Moon outpost for eight people, 1500 m^3.

SUMMARY AND REMARKS

From the preceding discussions, the following conclusions have been tentatively drawn. First, the water requirement in the Moon outpost is about (100 l per person) per day. Second, the crew should be as small as possible: the stability of the CELSS indicates a minimum of four, while good human relations are obtained with five or six people, and tasks on the Moon outpost require six technical experts and two scientists; therefore, the outpost crew should have eight members. Third, the outpost should have 1500 m^3 space for eight people.

The data upon which the above results are based contain uncertainties and assumptions, as discussed earlier. It is not the intention of the present paper to calculate the minimum crew number but to suggest that the Moon Park facilities be used as a research center where the fundamental data are obtained for the design of a Moon outpost.

Sociological factors have not been discussed here, yet they are essential. Different designs may be considered depending on whether a single international lunar base will be constructed or whether each nation will have its own lunar base. Crews made up of individuals with different backgrounds and cultures may affect the design and development approach taken for the lunar base. For these reasons, Moon Park as shown in Fig. 7 should be of an international nature and open to international participants.

REFERENCES

Architectural Institute of Japan (1980) *Architectural Design Information, 3*, p. 57. Maruzen, Tokyo.

Connors M. M. et al. (1985) *Living Aloft*, p. 61. NASA SP-483.

Nishibori E. (1958) *Memoirs of the Japanese Antarctic Wintering Party.* Iwanami Shoten, Tokyo. 269 pp.

Ogawa Y. (1985) Application of waste water recycling facility. Paper Presented to the 12th CIB-W62 Symposium. 21 pp.

N93-14016

LUNAR STEPPING STONES TO A MANNED MARS EXPLORATION SCENARIO

W. L. Davidson and W. R. Stump

Eagle Engineering, Inc.
16915 El Camino Real, Suite 200
Houston TX 77058

The initial trips to Mars by humans will be the first real severing of our dependence on Earth's environment. Common sense dictates that a human departure from Earth measured in years, to explore a distant planet, requires systems, techniques, and operations that have solid credibility proven with space experience. The space test and verification experience must occur with Mars-like conditions but under proving-ground conditions with good instrumentation, close monitoring, and fast emergency recovery capabilities. The lunar environment is the only arena that satisfies the requirements of a space planetary proving-ground. The objective of this scenario is to demonstrate a program planning approach that has human presence at Mars as the goal but, prudently, capitalizes on manned lunar project facilities, operations, and experience to enable a safe journey for the first Mars crew. The emphasis in lunar application objectives is to perform productive science and resources exploitation missions. Most of the Mars mission aspects can be proven in the lunar environment providing "stepping stones" to conducting the first human mission to travel to Mars and return safely to Earth.

SCENARIO STRATEGY

The Mars trip is measured in years, which presents the major challenge in implementing the scenario missions. We do not have space systems now that can perform and sustain human life away from our home planet for years. In addition, immediate help will not be available from experts on Earth for emergencies. The distance is so great that communications can take 15 to 20 minutes to receive a response. We have been to the Moon and the successful achievement of the activities in the Apollo program was awesome. Many new systems and operations had to function perfectly in the lunar trips, but the path to Mars is much more difficult.

The strategic goal for this combined lunar-martian exploration scenario is to extend human presence to Mars, while also returning to the Moon, with applications emphasis on science and resources exploitation. The strategy for implementing this goal is to be conservative relative to risk, bold in the extent of the Mars vehicle exploration capability, and cost effective in the use of common space systems and planetary resources. Because of the difficulties of the Mars objective, credible planetary systems, i.e., ones proven with extensive space experience, are required. That is, the systems used in the Mars journey must be ones with which the crew will be comfortable—like an "old friend" that has stood the test of time. The Moon can be used as a planetary proving-ground where systems common to Moon and Mars exploration are used productively and improved in design as a result of rigorous application. The plan is to use the safe (relative to the martian environment) lunar environment to learn planetary operations while conducting productive science and resource objectives. Based on this foundation of lunar experience, humans will separate from Earth for extended exploration at Mars. Building on the combined lunar and martian experience, planetary systems will continue to be developed, planetary resources utilized, and a human colony initiated on Mars.

The combined lunar-martian exploration scenario has been developed at a conceptual level. The general mission concepts for the lunar and martian flights are described in sufficient detail to identify the vehicles and major operations involved. A program of flights is synthesized to meet the goals of the scenario and developed into a flight schedule. An initial analysis has been performed to define the effort required to implement the scenario flight schedule. At this conceptual level, the support effort is measured in terms of the mass that must be delivered to low Earth orbit (LEO).

GUIDELINES AND ASSUMPTIONS

The central guideline for the scenario is to plan designs that exclude use of controversial technology leaps, minimize the Mars-bound vehicle initial weight prior to transmartian injection, use common systems, and provide schedule and configuration flexibility. The following assumptions are necessary to develop the combined lunar-martian exploration scenario:

1. A heavy lift launch vehicle is available for use to deliver approximately 100,000 kg per flight to LEO.
2. Chemical rocket engines are the baseline propulsion system for transplanetary propulsion and are assumed until specific trade analyses indicate a change is advantageous. Liquid oxygen and hydrogen are used in the engines for translunar and transmartian injection.
3. Artificial gravity habitation during transplanetary cruise is the baseline gravity habitation environment until trade analyses indicate a change is advantageous.
4. Aerocapture at Mars and Earth arrivals for savings in propellant is a baseline transportation technique until trade analyses indicate a change is advantageous. However, aerocapture must be flight verified to be as credibly safe as propulsive deceleration.
5. It is assumed that no significant water is discovered on the Moon.

6. Extensive operational applications of automated systems to control the manned spacecraft will be standard operating procedure.

7. Human planetary systems must be proven in rigorous operational use before application with human flight to Mars.

8. Human space flight in the lunar environment is sufficiently controllable to be safe for use as a planetary systems proving-ground.

9. Science objectives are pursued at the Moon on a noninterference basis with the planetary technology development objectives. In many cases, the two objective categories are mutually supportive.

10. Mars flights are conjunction class missions.

11. The Mars missions are sized to accomplish significant exploration on each trip.

12. It is assumed that Phobos is discovered to have materials usable for the production of propellant.

MISSION CONCEPTS

The mission concepts for the lunar and martian flights have many commonalities in the systems and operations to be performed. The flights in each planetary environment are generally defined in the following paragraphs.

Travel to the Moon is based on use of a reusable Orbit Transfer Vehicle (OTV). The components of the lunar flight concept are illustrated in Fig. 1. In this scenario, two OTVs are stacked with the payload mated to the second-stage OTV. A transportation staging node is required in LEO to assemble and launch the missions to the Moon. The LEO node consists of two Planetary Habitation Modules (PHMs) rotating about a central hangar to develop artificial gravity. Artificial gravity is used to gain experience for the Mars mission and to enhance propellant transfer. The first-stage OTV returns through the Earth's atmosphere using aerocapture techniques to return to the LEO node. The second-stage OTV and payload insert into a low lunar orbit (LLO). A variety of missions are conducted from this point in the generalized mission profile. The most common mission is the descent of a reusable Moon Flight Vehicle (MFV) to the lunar surface. On the lunar surface, crews perform science, construction, and resource exploitation work. They use surface transportation vehicles, both unpressurized and pressurized, to extend their range of operation. The Local Transportation Vehicle (LOTRAN) is unpressurized while the Mobile Surface Applications Traverse Vehicle (MOSAP) is pressurized and capable of long-range excursions. The MFV departs from the lunar surface to rendezvous with the OTV in LLO. The OTV carries the crew and/or payload through trans-Earth flight and aerocapture back to the LEO node. In another flight, the Mars Lander habitation module is delivered to the lunar surface and provides the first lunar outpost. Later, a permanent science outpost is constructed utilizing the PHM and other Mars-destined components. About this time, lunar oxygen is produced and used for all lunar descent and ascent flights. This phase of the scenario requires that Earth hydrogen be brought from the Earth and accumulated in an LLO propellant depot. The depot implementation is based on use of the PHM. The MFV is also used in LLO for moving between orbits and maneuvering space elements.

The Mars flight is a conjunction class mission. Departure is from the LEO staging node. The Mars mission vehicle crew quarters and operations center are in two PHMs implemented in an artificial gravity configuration. The Mars mission vehicle passes through the martian atmosphere upon arrival for an aerocapture transfer into a 24-hour elliptical orbit. The components of the Mars flight concept are illustrated in Fig. 2. Multiple Mars landings are included in each Mars trip. An expendable Mars Lander carries the crew and payload to the planetary surface direct from the 24-hour orbit using aerobraking and parachutes. In exploration visits of approximately 60 days each, crews perform science, construction, and resource exploitation work. They use the LOTRAN and MOSAP to extend their range of operation on the surface. The expendable Mars ascent stage takes the crew and payload to low Mars orbit. An MFV transfers from the Mars mission vehicle in the 24-hour orbit to the low Mars orbit to retrieve the surface crew and return to the Mars mission vehicle. The MFV is also used in independent flights to Phobos and Deimos where crews perform science and resource exploitation work. In later missions, PHMs are delivered to the martian surface to facilitate extended human presence. Development of oxygen on Phobos is included in the final stage of this scenario. The return to Earth is a continuation of the conjunction class mission. On approach to Earth, the crew transfers to an aerocapture module and separates from the large mass of the mission vehicle. The Mars mission vehicle is expendable and continues beyond Earth while the crew returns to LEO.

LUNAR STEPPING STONES

In this scenario, we return to the Moon and use it as the proving-ground for planetary technologies and experience that enable a safe journey to Mars. The lunar achievements providing

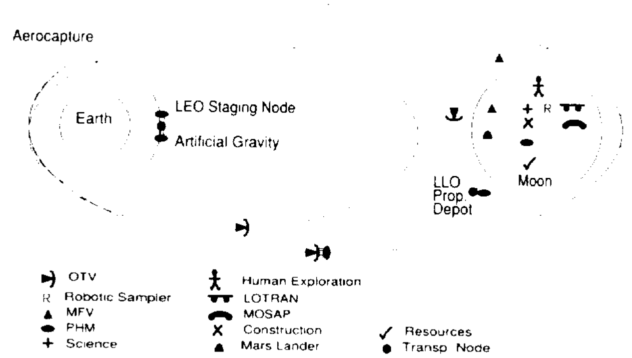


Fig. 1. Lunar flight concept.

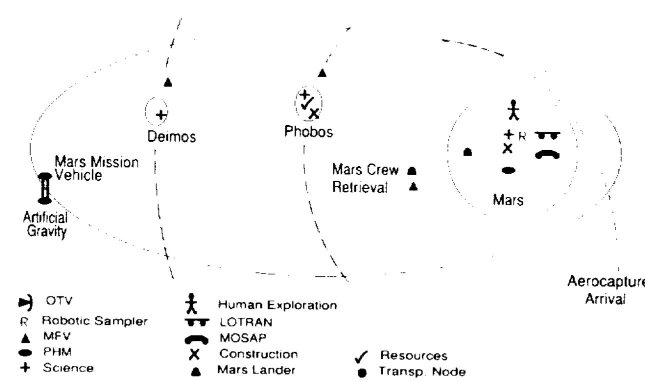


Fig. 2. Martian flight concept.

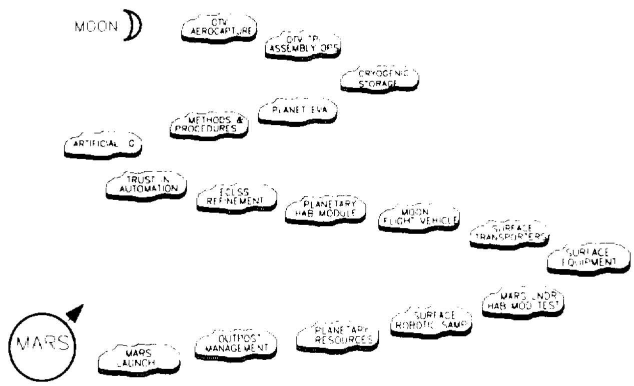


Fig. 3. Lunar stepping stones to Mars.

stepping-stones in the path to Mars are illustrated in Fig. 3. These steps common to both the lunar and the martian exploration fall into two broad categories, systems and operations. Both categories are identified in the following paragraphs, starting with the one that is less often considered, but is potentially more critical.

The common operations, methods, and procedures that can be learned in the lunar environment and must be mastered before attempting Mars exploration are (1) in-space planetary vehicle assembly and transplanetary injection operations, (2) EVA-based planetary field operations, (3) on-site planetary science and sample analysis methods and procedures, (4) planetary construction methods and procedures, (5) artificial gravity environment verification and operations adaptation, (6) trust in automated and computer-controlled systems operations, and (7) planetary outpost site management techniques and procedures.

Planetary systems having common systems design criteria for performance in the lunar and martian missions are (1) aerocapture structures, materials, and vehicles, (2) cryogenic propellant in-space storage and transfer systems, (3) artificial gravity systems, (4) life support systems refinements, (5) planetary habitation module, (6) Moon Flight Vehicle, (7) Local Surface Transportation Vehicle, (8) Mobile Surface Applications Traverse Vehicle, (9) surface equipment for science and construction, (10) Mars lander habitation module, (11) planetary surface robotic sampler, and (12) planetary resources plant equipment.

FLIGHT SCHEDULE

Using the strategy of this scenario, the stated assumptions, the space elements identified in the mission concepts, and the common requirements in the stepping-stones, a scenario flight schedule has been developed. The schedule, which includes calendar years 2001 through 2025, is provided in Fig. 4. However, prior to 2001, a number of important precursor missions have occurred. Automated missions have been flown to the Moon and Mars. The MFV has been flown in LEO with crews for flight test and verification. The PHM has been flown for one year to verify systems design and operation in LEO using a zero-gravity mode.

The sequential flow of flight activity shown in Fig. 4 begins with the orbiting of a second PHM and artificial gravity systems to combine with the initial PHM. This PHM configuration is flown for one year as an experiment and verification of artificial gravity habitation. Also in 2001, the first humans return to the lunar surface using the MFV in the final flight verification of the vehicle. At the conclusion of the one-year artificial gravity verification flight, the PHM configuration is expanded with additional systems from Earth into the LEO transportation staging node. In 2002, local lunar science is initiated and performed in a two-year series of MFV exploration flights. A four-year series of MFV outpost exploration flights begins in 2004 with the delivery of a Mars Lander habitation module to the lunar surface. During this period, a two-year operation of a lunar oxygen pilot plant is accomplished producing 2000 kg of liquid oxygen per month. In 2007, annual missions are started to the farside of the Moon to perform observatory objectives. The following year, a LLO propellant depot is established to store liquid hydrogen from the Earth in preparation for lunar flight operations using lunar oxygen. The oxygen production plant is delivered and constructed on the lunar surface in 2009 and starts production leading to 20,000 kg per month. The construction of a science outpost begins in 2008 and continues in operation with MFV support for the duration of the scenario. It is projected that the potential for exporting lunar resources will not occur until the closing of this scenario period.

The first Mars mission leaves on the 2007 opportunity. This first human flight will stress total environment investigation (four surface expeditions, human visits to Phobos and Deimos, numerous automated probes, and extensive orbit observations). The transportation system is designed to deliver a base to the surface of Mars over a long series of missions. It is, therefore, oversized for the first manned mission. A mission is not planned at the next conjunction class opportunity to allow adjustment to the first mission experience. Thereafter, a mission is flown at every conjunction class opportunity. The mission objectives are gradually expanded from local science, to regional science, to resources emphasis, and, finally, to preparing for a self-supported Mars surface base.

SUPPORT ANALYSIS

It is important to consider the impact on national resources of supporting a particular scenario. Since the scenario has been synthesized at a conceptual level, it is not possible to estimate the required support resources or dollar cost. An available measure of support impact that is closely related to the eventual cost budget is the mass required to be delivered to LEO to

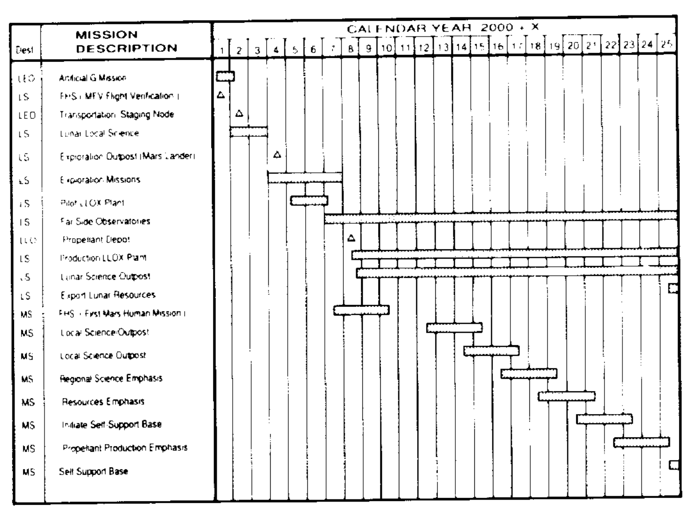


Fig. 4. Flight schedule for combined lunar-martian exploration scenario.

operate the scenario missions. The flight schedule provided in presentation form in Fig. 4 was developed in a computer spreadsheet with individual flights and estimated masses of the flight elements. The spreadsheet was designed to accumulate the masses by year and by various scenario elements. The resulting mass schedule has been summarized in Figs. 5-9. Figure 5 shows the payload mass delivered to the lunar surface on a yearly basis. The low mass in 2006 is an intentional gap to accommodate preparations for the first Mars mission. The high peak masses in the years 2004 through 2010 reflect the impact of establishing the initial lunar facilities. The bar chart in Fig. 6 requires special interpretation due to the methods used in the spreadsheet and the long duration of the conjunction class Mars missions. Each Mars mission vehicle stack is assembled in LEO over a two-year period. The Mars payload mass is entered on the schedule divided into the two years prior to arriving in Mars orbit. For example, the payload mass for the first mission in 2007 is approximately 500,000 kg. The line graph in Fig. 7 can be interpreted as showing two points. First, the surface payload mass for both the Moon and Mars are in the same order of magnitude. The second observation is that the lunar surface payload accumulation leads the martian payloads early when the lunar facilities are being established, but the later mass to establish martian surface facilities is greater. Two reasons for the greater martian mass are that the expendable landers are considered as surface payload and two martian bodies are receiving surface facilities (Phobos and Mars). Reusable landing vehicles are much easier to build for the Moon than for Mars due to the atmosphere. Figure 8 is a stacked bar chart that records the total annual mass delivered to LEO in support of this scenario. The bars identify the components due to each of the Earth orbit, the lunar, and the martian activities. The direct Earth orbit masses are relatively insignificant. The initial peaks in 2004 through 2009 are due to the combined requirements of the emplacement of the lunar surface facilities and the support of the first Mars mission. In later years, the annual mass for the Mars support appears to overshadow the lunar support. However, Fig. 9 shows that the apparent imbalance is less when viewed over a longer time period. This line graph plots the cumulative mass delivered to LEO in support of this scenario. In this view, the lunar and the martian accumulated LEO mass can be seen to be in the

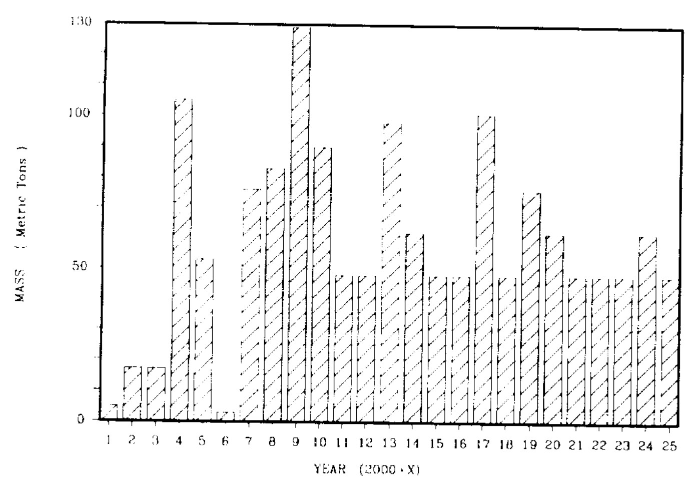


Fig. 5. Annual payload mass to lunar surface.

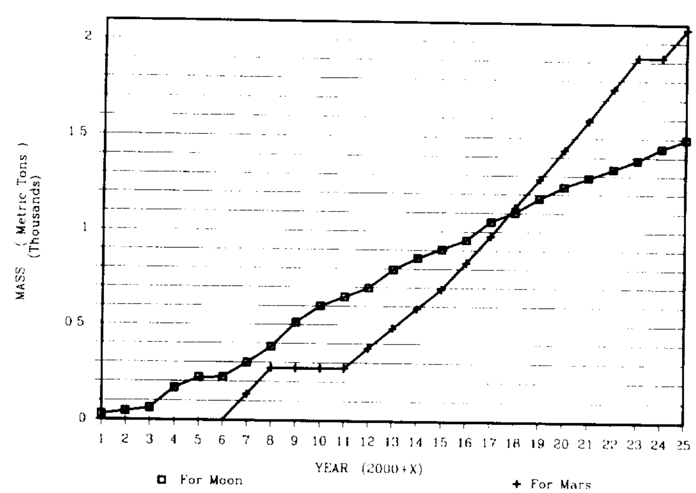


Fig. 7. Cumulative mass to planet surface.

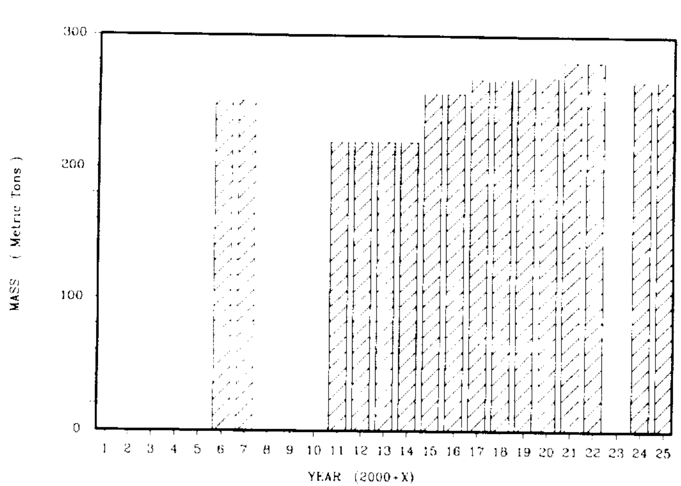


Fig. 6. Annual Mars orbit payload mass launched to LEO.

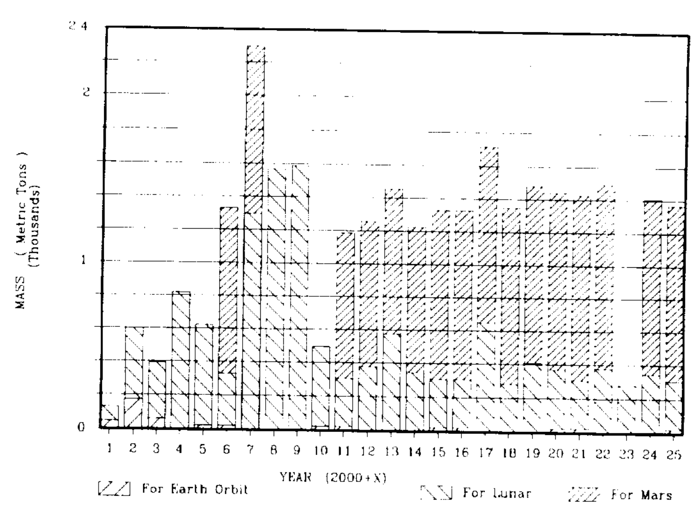


Fig. 8. Annual mass required in LEO.

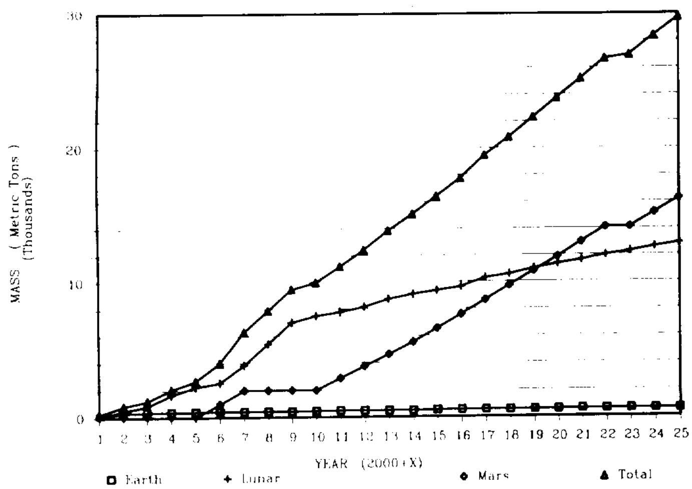


Fig. 9. Cumulative mass required in LEO.

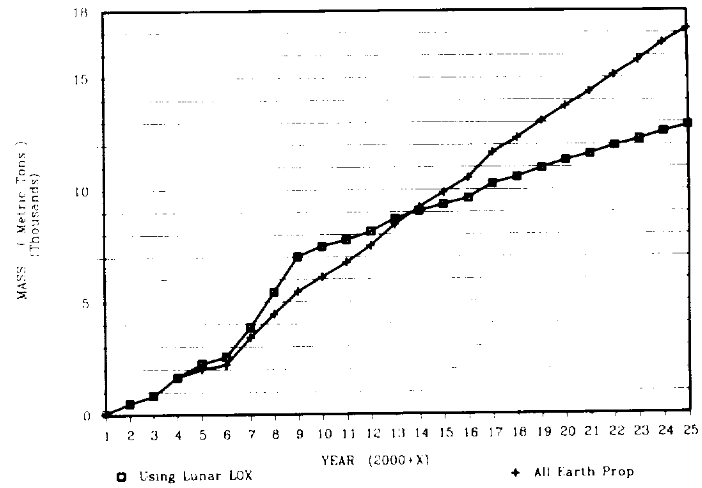


Fig. 10. Reduction in cumulative mass required in LEO using lunar oxygen.

same order of magnitude. In fact, it is 2019 before the martian numbers exceed the lunar support. An additional point is that the lunar support LEO mass required has been reduced through the use of lunar resources while the martian resource usage benefit has not yet come into operation.

It is important to reduce the mass required to be delivered to LEO in support of this scenario in order to lower the program cost. The required mass in LEO can be reduced by various approaches; as an example, the amount of LEO mass reduction can be shown for a method used in this scenario. The plant producing oxygen on the lunar surface begins operation in 2009. Figure 10 plots data indicating the reduction in cumulative mass required in LEO when using lunar oxygen. The plot for the scenario using lunar oxygen (squares) indicates a high rate of mass accumulation until 2009 while related facilities are implemented. At this point, lunar oxygen utilization begins and a knee in the plot verifies a reduced rate of LEO mass accumulation. The plot for the same scenario application missions, but no use of lunar oxygen or implementation of facilities related to lunar oxygen production is marked with plus symbols. The plot demonstrates that there is less LEO mass required in the early years, but by 2014 the cumulative savings when using lunar oxygen cause the plots to diverge. Other potential approaches to reducing required mass in LEO include lunar oxygen delivered to LEO, Phobos oxygen production and use at Mars, martian oxygen production and use at Mars, martian mission departure from the lunar vicinity, and use of more advanced propulsion systems. These other approaches should be investigated, but were not developed in this scenario. The development of Phobos oxygen in the closing years of the scenario time period was included, but the beneficial effects would not be realized until the self-supported Mars base phase following this scenario.

SUMMARY

In summary, a combined lunar-martian scenario has been developed. The goal of the scenario is to extend human presence to Mars and to return with humans to the surface of the Moon for extensive applications in science and planetary resources exploitation. The common links between lunar and martian exploration have been described and referred to as lunar stepping stones in the path to Mars. A methodology has been developed for planning, implementing, and assessing planetary exploration scenarios. The impact of implementing the missions in the scenario has been reviewed in terms of the mass required to be delivered to LEO to support the scenario operations. The data demonstrate that these lunar and martian activities require resources on the same order of magnitude. It has also been shown that simple use of lunar oxygen can provide visible reductions in required program resources.

It is imperative that the first human journey to Mars return safely to Earth. This success requires that all systems and operations be proven in previous, repetitive program activities. The Moon is the only suitable planetary proving-ground and provides exciting opportunities for exploration on its own merit. A program to develop the described lunar stepping stones to Mars should be developed in more detail. The Mars trip may be the challenge, but the success of the journey will be determined on the Moon.

CREATING A FOUNDATION FOR A SYNERGISTIC APPROACH TO PROGRAM MANAGEMENT

Karyn T. Knoll

Lunar and Mars Exploration Office
Mail Code IZ
NASA Johnson Space Center
Houston TX 77058

Previous large, multicenter NASA programs have been accomplished by dividing the program into elements (e.g., command module, Saturn V booster, Orbiter) that were designed, developed, and integrated by a prime contractor under the management of a single NASA center. While this method minimized the managerial complexity of a given program, it created an organizational structure within the agency that makes it difficult for new NASA programs to effectively use hardware and resources developed for previous programs. Therefore, each new NASA program must essentially start from scratch. In order to accelerate the movement of humans into space within reasonable budgetary constraints, NASA must develop an organizational structure that will allow the agency to efficiently use all the resources it has available for the development of any program the nation decides to undertake. This work considers the entire set of tasks involved in the successful development of any program. Areas that hold the greatest promise of accelerating programmatic development and/or increasing the efficiency of the use of available resources by being dealt with in a centralized manner rather than being handled by each program individually are identified. Using this information, an agency organizational structure is developed that will allow NASA to promote interprogram synergisms. In order for NASA to efficiently manage its programs in a manner that will allow programs to benefit from one another and thereby accelerate the movement of humans into space, several steps must be taken. First, NASA must develop an organizational structure that will allow potential interprogram synergisms to be identified and promoted. Key features of the organizational structure recommended in this paper include (1) the establishment of a single office to perform the mission analysis and system engineering functions across all NASA programs and, therefore, to replace the performance of these functions as part of each individual program; and (2) the establishment of technical discipline agents to perform subsystem management on an agency-wide basis, as opposed to having each NASA center provide its own subsystem managers to support the development of those elements for which the center is responsible. Second, NASA must begin to develop the requirements for a program in a manner that will promote overall space program goals rather than achieving only the goals that apply to the program for which the requirements are being developed. Finally, NASA must consider organizing the agency around the functions required to support NASA's goals and objectives rather than around geographic locations. If we are serious about moving toward the permanent presence and expansion of humans into space, NASA must organize itself to be able to treat the space program as a program rather than as a collection of individual initiatives.

During the early years of the Space Age, American endeavors in the area of manned spaceflight were generally accomplished through a series of relatively independent programs with fairly specific and well-defined goals. Often these programs were developed by dividing the program hardware into elements (usually, manned spacecraft elements and booster elements) that were designed, developed, and integrated by a single (prime) contractor under the management of a single NASA center. In 1988 President Reagan announced a "Space Policy and Commercial Space Initiative to Begin the Next Century," which contained the following major components: (1) establishing a long-range goal to expand human presence and activity beyond Earth orbit into the solar system; (2) creating opportunities for U.S. commerce in space; and (3) continuing our national commitment to a permanently manned space station.

In order to accomplish the ambitious, broadly defined kinds of goals that this policy set for the nation, NASA must be capable of undertaking a variety of highly interactive and dynamic programs with goals that will change and develop as each of these programs is defined and realized. Because the existing NASA organizational structure was developed to enable the agency to respond to programs of a specific, well-defined nature, it is desirable to review this structure in terms of its capability to respond to the kinds of challenges that NASA will be undertaking in order to fulfill the charges of the national space policy. This paper examines the organizational structure currently in existence for the implementation of NASA programs, and proposes an agency architecture structured to provide the flexibility NASA requires in order to efficiently accomplish the kinds of programs involved in the achievement of our national goals in space.

Figure 1 presents an overview of the flow of the major functions involved in the development of a typical program. (For the sake of clarity, this flow is presented in a very basic and straightforward manner. The actual process, however, is highly interactive and iterative.) The mission analysis function collects the necessary data and performs the analyses required to transform the top-level goals and constraints for the program into a set of quantified requirements that tells the engineers responsible for designing the

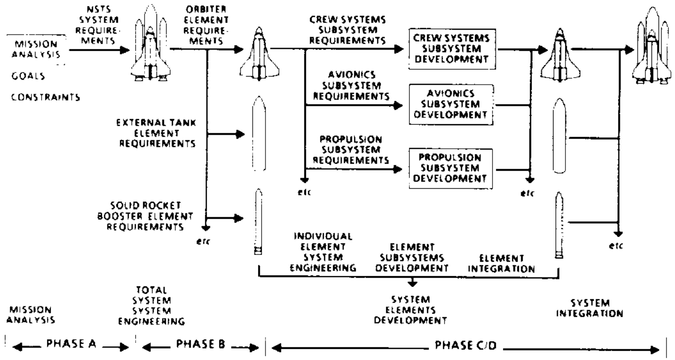


Fig. 1. Overview of the flow of a program.

system, in specific terms, just what they are supposed to design the system to be able to do. The mission requirements, which are output as the product of the mission analysis activity, serve as an input to the system engineering function of the total system that defines the configuration of the most efficient (lowest total cost) system capable of meeting the performance parameters specified by the mission requirements. To "define" the configuration of the system means to determine and specify the elements that compose the system, along with the requirements on each of these elements. The word "element," as used in this paper, refers to an essentially modular part of the total system in which the subsystems are relatively self-contained. Usually, though not always, this "modular, self-contained subsystems" property of an element is caused by the fact that the element functions as a separable, independent unit during some phase of the mission. The command module, the lunar module, the Saturn V booster, and the solid rocket boosters are all examples of elements. Although it does not separate during the mission, the main engines module of the space shuttle is also considered to be an element since it does fit this modular, self-contained subsystems definition. Additionally, this element is treated as an independent unit during processing. Under the above definition of an element, the mannedcore portion of the space station would be considered to be a single element that is divided into several subelements for development and assembly purposes.

The element requirements output by the total system system engineering function serve as input for the element development phase of the program. During this phase, elements that meet the element requirements are developed. In the accomplishment of this activity, the following major functions are performed for each element of the program.

1. Individual element system engineering that defines the configuration of the element that is most capable of meeting the requirements output by the total system system engineering function; to "define" the configuration of an element means to determine and specify the requirements on each subsystem (including the element unique equipment, which is also treated as a subsystem during this analysis) of the element.

2. Subsystems development that develops each subsystem in accordance with the subsystem requirements defined by the individual element system engineering function.

3. Element integration that combines the developed subsystems into an element that meets the requirements levied on the element by the total system system engineering function.

The final major function that must be performed in support of the development of a typical program is the system integration function, which combines the developed elements into a total system that meets the requirements levied on the system by the mission analysis function.

To accomplish the earlier major, manned programs for which NASA was responsible, such as the Apollo and space shuttle programs, NASA, together with its Phase B contractors, performed the total system system engineering function, which defined the elements constituting the total system and produced a set of requirements on each of these elements. These requirements were then used to write the Phase C/D requests for proposal (RFPs) for the development of these elements. Generally, one contract was awarded for each of the elements to be developed. This contract included responsibility for the performance of all the functions involved in the development of the element: the system engineering function that defined the requirements on the subsystems of the element (note that here the "system" referred to in the system engineering function is the element), the development of all the subsystems of the element, and the integration of these subsystems into an element. In addition to the element contracts, an integration contract (or a separate schedule) was awarded for the integration of the developed elements into a total system. This integration contract did not include any responsibility for the integration of an element's subsystems into the element. This type of element integration was handled as part of the contract for the development of each element.

The development contract for each element of a program was managed by a single NASA center. Additionally, each element of the earlier major, manned NASA programs could generally be related to some major function—propulsion, crew support (manned spacecraft), communications, or operations—required for the accomplishment of the program. For the Apollo program, as shown in Fig. 2a, centers were set up to provide expertise in these areas. Because the space shuttle was composed of elements with these same functions, the space shuttle program could be smoothly managed using the same structure that the agency developed in order to accomplish the Apollo program (Fig. 2b).

With the undertaking of the space station program, NASA assumed responsibility for the development of a program that could not be divided into a set of Apollo-like elements. In fact, as Fig. 3 illustrates, by the modular, self-contained subsystems definition of an element, the mannedcore space station is really a single element that has been divided into several subelements for development and assembly purposes. Since, in the case of the mannedcore space station, the element equals the total system, only the "inner loop" functions shown in Fig. 1, those associated with the development of a single element, are performed for the mannedcore element of the space station program. In order to handle this situation, NASA had to choose between awarding a single contract for all the functions—system engineering, subsystems development, and element integration—involved in the development of the mannedcore space station element, or changing the architecture of the agency enough to enable NASA itself to assume responsibility for the performance of these functions. The first option would allow NASA to develop the mannedcore space station element using the same programmatic methodologies the agency already has in place as a result of supporting its past programs; the second would incorporate some of the element development procedures formerly performed by the prime contractor for an element and would force NASA to manage

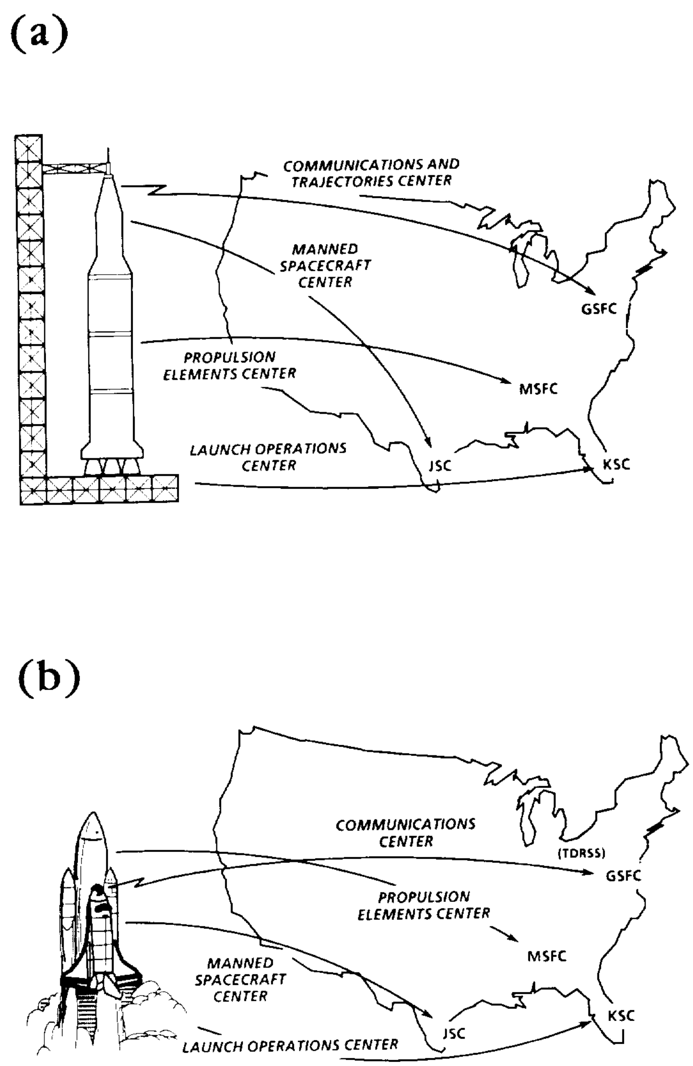


Fig. 2. **(a)** In the beginning: The Apollo program. **(b)** Continuing the tradition: The space shuttle program.

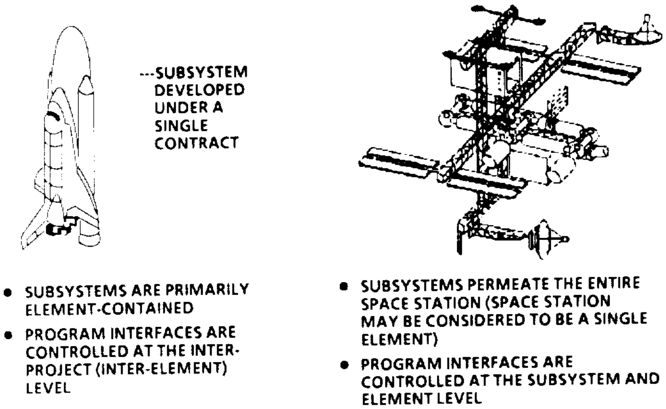


Fig. 3. Today's programs: A new way of doing business.

the contracts for the accomplishment of some of the specific activities (such as the development of a particular subsystem) involved in the development of an individual element. Previously, under the single contract method, the prime contractor for the element awarded and managed subcontracts for the performance of these element development tasks.

As NASA undertakes the programs required for the achievement of our national goals in space, it will assume responsibility for the development of many different types of aerospace systems—cargo and personnel transports, spaceports, surface habitats of both a temporary and a permanent nature, mining facilities, and so forth—that may not easily divide into manned spacecraft and booster-type elements for development purposes. In fact, as has already been illustrated, some systems may not efficiently divide into elements at all. In order to meet the challenges of the future, NASA will require an agency architecture that is flexible enough to support the development of a large variety of different types of aerospace elements.

Additionally, each major, manned program undertaken by NASA has been the focus of attention of the agency for the duration of the program and has usually been completed before the development of the next major program was begun. Because past programs had fairly specific goals, each program could generally be structured as a means to the accomplishment of a limited set of objectives that terminated (or passed over from a development to an operational phase) when this set of objectives was achieved. For this reason, previous NASA programs were accomplished relatively independently of one another. The most notable exceptions occur in programs such as Apollo-Colo3 and Skylab that used hardware from a previous program. Even these programs, however, are simply cases of making use of already existing hardware rather than being examples of any type of "global" planning across several programs. (That is, the hardware was custom designed for the initial program. Later programs were then "forced-fit" to be able to make use of this existing hardware instead of designing the initial hardware to be the optimum hardware for all the programs that were expected to use it.)

In order to accomplish the broad, long-range kinds of goals specified by the national space policy, NASA will have to define, develop, and undertake sets of highly interactive programs that together achieve a high-level goal. As illustrated in Fig. 4, a lunar colony may consist of lunar science facilities, observation equipment for studying the universe, and a LOX facility that will provide propellants for transports to Mars. Although this colony is composed of elements that are satisfying the objectives of three different programs, it may be beneficial to design the colony so that the crew members supporting these elements all share the same habitat (and the same logistics support) and so that the elements all receive their power from the same power facility. Though developed under a number of different programs, the entire set of elements shown in the figure efficiently achieve the goal stated in the national space policy of "establishing a long-range goal to expand human presence and activity beyond Earth orbit and into the solar system." In order for the entire colony to function smoothly, all the elements of the lunar colony would have to be designed to "play together" as components of a single system. Additionally, the elements of this lunar colony would have to be capable of smoothly interfacing with the elements of the programs of which they are a part; i.e., the lunar observatories may have to coordinate with other Earth- or space-based equipment in order to provide complete data required for a

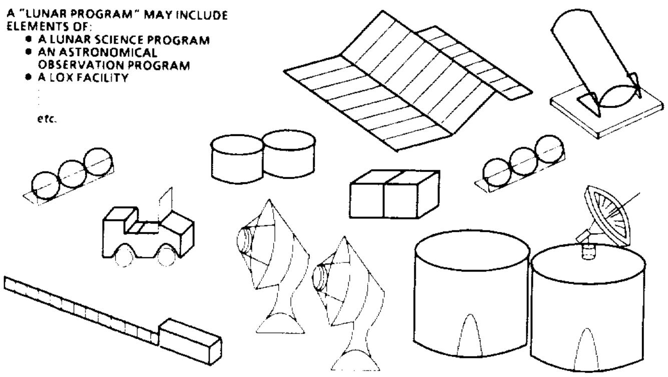


Fig. 4. The interactive nature of potential future programs.

particular astronomy experiment, the LOX facility will have to function in cooperation with the Mars transport vehicles for which it provides propellants, the entire colony must be able to interface with its resupply and logistics support network, and so forth. If NASA plans to undertake this type of ambitious scenario in the future, it will be necessary for the agency to develop the capability to define the requirements for each of its new programs in a manner that enables these programs to efficiently interact with the other agency programs and thereby promotes the overall goals of the space program rather than in a manner that will achieve only the goals of the individual program for which the requirements are being defined.

In summary, in order to achieve the goals that the U. S. has set for itself in space, NASA will require an architecture that enables the agency to: (1) develop the requirements on the elements of future agency programs in a manner that recognizes and accounts for the interactions that need to take place in order for the elements of these programs to function together as part of a single, coordinated, space program; and (2) handle the development of a variety of different types of elements.

In past programs, the system under development was optimized to achieve a set of mission requirements that were specific to the program itself. Any interactions with other programs could generally be handled as external interfaces with already developed systems (thereby making these interfaces very specific; such interfaces could generally be handled as being constraints on the program). Anticipated interactions, or optimum trade-offs, with elements of projected future systems were rarely considered. Instead, when such future programs did reach the development stage, they would handle any necessary interactions with the previous program as being constraints on the new program. This situation meant that a system could be defined by considering only those interactions taking place between the elements of the system itself. If, however, NASA now plans to begin serious consideration of the interactive types of programs required for the achievement of the ambitious kinds of goals specified in the national space policy, it will be necessary to consider the interactions and optimum trade-offs occurring between the elements of a number of systems that will be developed at different times under different programs. This new set of circumstances suggests that those functions leading to the definition of the elements of a given program—the mission analysis and total system system engineering functions (refer to Fig. 1)—should be replaced by a function that analyzes the interactions and optimizes the trade-offs between the elements of all the programs (or potential programs) that make up the nation's space program. This situation, illustrated in Fig. 5, implies that NASA should consider replacing the mission analysis and total system system engineering functions previously performed as part of each individual agency program with a single "program engineering" (where "program" here refers to the whole space program) function that serves the entire agency. An agency program engineering office should be set up to implement this function.

Although an explanation of the program engineering process is beyond the scope of this paper, a few points should be mentioned. The program engineering process is basically a system engineering process in which the "system" under analysis is the entire space program. Beginning with broad categories of missions that offer the potential for furthering our national goals in space (for example, perform a thorough scientific study of the Moon, study the universe beyond our solar system, perform a thorough scientific study of Mars, and so forth), the specific experiments and processes (or candidate options for experiments and processes) required for the accomplishment of each mission category are identified. The mission analyses and system engineering studies required to accomplish this set of experiments and processes are performed in such a manner that any synergies and beneficial trade-offs between these mission activities and the systems designed to support their implementation are identified. (The program engineering process would identify, for example, that some of the equipment used to perform observations of the universe can, or should be, lunar-based, and that the crew members required to operate and maintain this equipment could share a habitat with lunar crew members performing lunar science experiments and those operating a LOX facility producing propellants for transports to Mars. The number, character (content or "set of elements"), and time-phasing of the most efficient set of programs leading to the accomplishment of the complete set of input mission categories is produced as an output of the program engineering process. Notice the "crossovers" that occur between input missions and the programs in which these missions are actually implemented. (Some of the observation equipment used to support the Study of the Universe mission category may be developed as part of a lunar program, and other

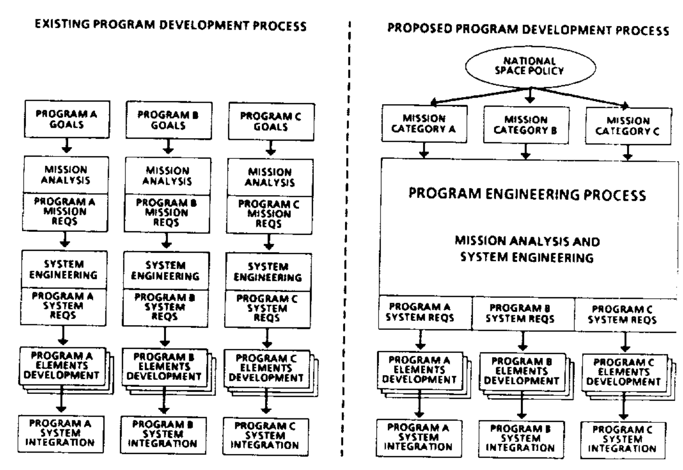


Fig. 5. NASA program development process.

equipment supporting such a mission may end up being developed as part of a low-Earth-orbit program; the LOX facility, though supporting a Mars mission, may itself be developed as part of a lunar program; and so forth.) Another important point that should be mentioned in regard to the program engineering process is that, although this process should be the responsibility of a single office (the agency program engineering office), it is not expected that all the personnel needed to perform this process would be located in that office. The agency program engineering office itself should direct and coordinate the studies and analyses required for the performance of the program engineering process and should interpret the results leading to the definition of the elements (and programs) needed to accomplish our national goals in space. The actual performance of the studies and analyses required to support the program engineering process should be performed by the NASA institution located at the field centers.

Although the establishment of an agency program engineering office for the performance of the program engineering function will enable NASA to define the elements of its programs in a manner that optimizes the interactions between these elements, the problem of determining an organizational structure that will allow the agency to efficiently develop any type of element defined as an output of this process still remains. Figure 6 suggests a solution to this situation by pointing out that all the elements defined by the total system system engineering function (or by the program engineering function that replaces it in the case of highly interactive programs) are basically composed of the same kinds (though not necessarily the same architecture) of subsystems.

As Fig. 7a illustrates, in managing the development of the elements of past programs, NASA used subsystem managers who were located at the same center as the project office for the element they supported and who developed expertise in the types of subsystems associated with that element. This meant that each center developed a pool of experts who were adept at understanding a particular set of subsystem architectures associated with the elements that had been developed at that center. During the Apollo program, which had the unique opportunity of structuring the agency to meet its needs (see Fig. 2a), and the space shuttle program, which resembled the Apollo program in terms of programmatic structure (see Fig. 2b), this subsystem manager arrangement worked well. However, as NASA moves toward a future that envisions expansions into new areas of space exploration and begins the undertaking of the programs required for the realization of this vision, it is very likely that the current approach to programs in which almost all the personnel

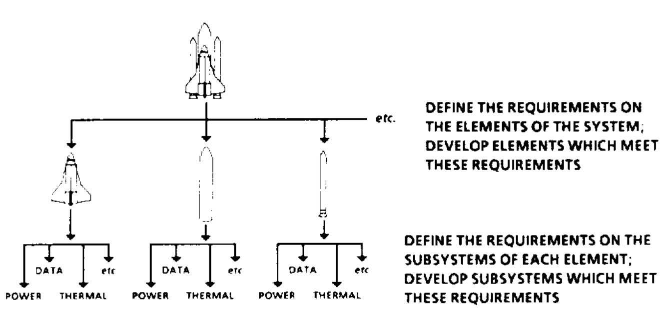


Fig. 6. Program definition and development.

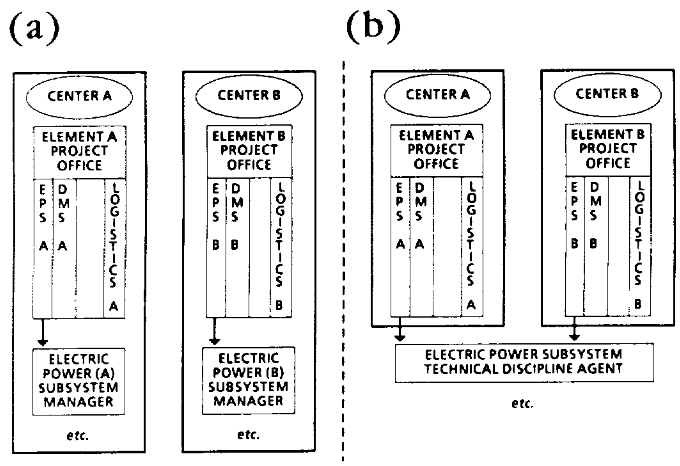


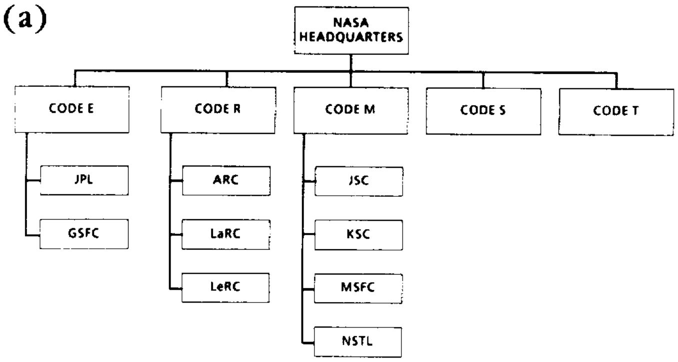
Fig. 7. Use of technical discipline agents for consolidation of subsystem management: **(a)** Existing subsystem management structure in which each center provides its own subsystem managers for every subsystem of the element(s) for which the center is responsible; **(b)** proposed subsystem management structure in which, for a given subsystem, the same technical discipline agent provides subsystem management for all elements in the agency.

(including the subsystem managers) associated with the development of an element work directly for the center responsible for the element will prove to be too inflexible to allow NASA to efficiently manage the variety of new programs the agency will be undertaking in the near future. One of the problems likely to be encountered in the future is the need to reassign personnel and to redirect the use of facilities that were involved in the development of a program after the program moved into its operational stage. This problem becomes especially acute when the center is not assigned responsibility for the development of a new element (which is one of the motivations behind the competition between centers that is sometimes observed during the assignment of the elements of a new program). Another problem that may be encountered is an unnecessary duplication of effort between different centers caused by the fact that, under the current NASA organizational structure, it is easier for a center to establish its own expertise in a particular technical discipline than it is to access already established expertise located at another center. Yet another potential problem is the probability of mismatches occurring between center expertise and the assignment of the development of an element to a particular center. Such mismatches are caused by the fact that in the past, when NASA assigned the development of an element to a center, this assignment included the development of all the subsystems within the element, even if the expertise in some of the subsystems was located at another center. As NASA begins to assume responsibility for the development of a large variety of elements, a situation develops in which the expertise in some of the subsystems of an element will be located at one center, while the expertise in other subsystems will be located at other centers. NASA must then solve how to assign the development of the element to a particular center while efficiently making use of all the center expertise, with its associated resources (test beds, research facilities, databases, and so forth) available throughout the agency. As Fig. 7b illustrates, one method of alleviating this situation is by establishing a technical discipline agent for each of the subsystems involved in the development of a typical aerospace element. These

agents are groups (possibly divisions or small directorates) of technical personnel set up to provide support in their technical discipline to any NASA program requiring such support, regardless of where the program or project office requiring the support was located. (In order to maximize the effectiveness of technical discipline agents, it is recommended that NASA investigate the feasibility of standardizing the types, though not the architectures, of subsystems associated with the development of any given element.) By eliminating the need for each technical discipline agent to be located at the same center as the office it supports, technical discipline agents offer one potential method for providing NASA with the flexibility it requires to support a variety of new programs. As one program ends or scales down for a period of time, the manager of a technical discipline agent can reassign the personnel who were supporting the program to new programs just beginning to require support. Such reassignments can be made regardless of where the project offices for the new program are located.

The establishment of an agency program engineering office and technical discipline agents are suggested as methods for the solution of specific problems expected to be encountered as the agency begins undertaking the kinds of programs involved in the achievement of our future national goals in space. Still remaining is the consideration of an organizational structure, with its associated lines of authority or management structure, which combines these concepts with the other functions required for the successful accomplishment of a program in a manner flexible enough to accommodate the development of any set of programs that the nation decides to undertake in space. Figure 8a illustrates the current NASA organizational structure in which all employees located at a given center, including those in any program or project office located at the center, are under the direct management of the director of the center. Each center is, in turn, under the management of a specific code. During the Apollo program, when centers were established to provide specific functions in support of the development of the program, and these functions were consistent with the responsibilities of the code that managed the center, such an organizational structure worked well; that is, the organizational structure was consistent with the structure of the program it was managing. Since the Apollo program, however, NASA has managed the development of an ever-increasing variety of programs. Taking on new kinds of programs without modifying the structure of the agency to be consistent with the needs of these new programs has left NASA with a structure that possesses significant gaps and inconsistencies in some of the lines of communication and authority involved in the implementation of its programs. For example, during Phase B of the space station program, the program manager did not answer directly to the associate administrator for the space station program (Code S). Instead, the program manager answered to the center director of the center at which the program office was located (the Johnson Space Center, in this case), who, in turn, answered to the associate administrator for manned spaceflight (Code M). The associate administrator for manned spaceflight and the associate administrator for the space station program were organizational equals, both of whom answered to the administrator. Similarly, there were no direct lines of communication between the program manager and the projects office managers for each of the work packages of the space station program. Each projects manager answers to the director of the center at which the projects office is located who, in turn, answers to the associate administrator of the code responsible for that center. Today,

(a)



(b)

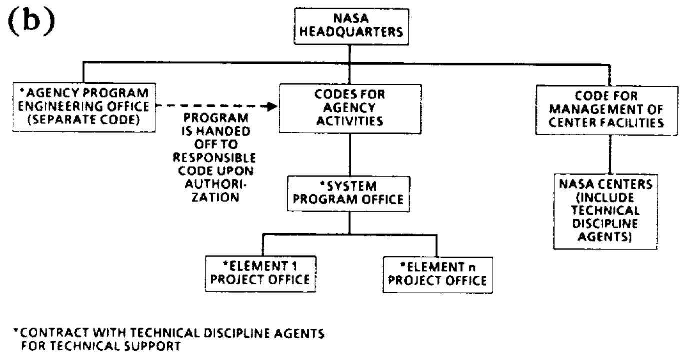


Fig. 8. **(a)** Existing NASA organizational structure; **(b)** proposed NASA organizational structure.

although the program manager (now called the program director) has been moved to the office of the associate administrator for the space station program, the lines of authority directing projects managers are still somewhat unclear. There are several similar situations throughout the agency in which personnel involved in the accomplishment of a program, which is the development responsibility of one code, work for a center managed by another code. The lines of authority in these cases are often somewhat ambiguous. This situation will certainly affect the agency's ability to efficiently manage the programs it will be undertaking in the future.

In order to provide more direct lines of authority between the agents involved in the implementation of future programs, this paper suggests that NASA consider employing an organizational structure like that illustrated in Fig. 8b. Under the arrangement shown in this figure, a program is developed through the Phase B level (that is, through to the determination of the requirements on the elements of the program) by the agency program engineering office, which is part of its own code, separate from the other NASA codes. Upon authorization of a particular program, responsibility for the program is handed off to the code that has been assigned responsibility for the development of the program. For example, responsibility for the development of an unmanned planetary exploration program may be handed off to Code E,

responsibility for the development of a manned program may be handed off to Code M, responsibility for the development of an especially large program may be handed off to a new code created for the management of its development (like the space station program), and so forth. Upon authorization of a particular program, the responsible code sets up a program office to manage the development of the overall program and a project office for each element of the program to manage the development of its respective element. Regardless of the location of each program or project office, all the personnel in the office answer directly to the program manager who, in turn, answers directly to the associate administrator of the code responsible for the development of the program. That is, all personnel in the program-related offices are badged to the NASA code responsible for the development of the program. (This situation is somewhat analogous to that employed by the Air Force in which all personnel under a particular Command are considered to be part of that Command regardless of the base at which they are physically stationed.) Additionally, Fig. 8b recommends the establishment of a new code to be responsible for the management of the facilities of all the centers in the agency. All centers would be managed by this code (i.e., all center directors would be under the authority of the associate administrator for this code), which, through its center directors, would be responsible for insuring that the personnel located at each center were provided with the proper resources and support required to accomplish their job, no matter which agency code they were attached to. Additionally, any personnel who were specific to the center, like the technical discipline agents located at the center, would be under the managerial authority of the center director who, in turn, would be under the authority of the associate administrator for the center management code. The technical discipline agents would provide technical support in their disciplines to all NASA program and project offices as well as to the agency program engineering office on a "contract for services required" basis. These technical discipline agents would provide the services previously performed by the subsystem managers in past NASA programs, as well as the support the agency program engineering office and the project offices will require in order to perform the program engineering and contract management functions for which they are responsible.

In conclusion, this paper attempts to provide a strawman architecture that addresses some of the new kinds of problems with which NASA will most likely be expected to have to deal as it undertakes the ambitious types of programs suggested by our national space policy. This proposed architecture has been developed by primarily concentrating on concerns that are specific to the successful development of NASA programs. In undertaking the development of a complete architecture for the agency, NASA will have to determine how the development of the programs for which the agency is responsible fits into the complete set of activities with which NASA is concerned. Any architecture adopted by the agency should, as a minimum, however, enable it to (1) determine the requirements on the elements of future agency programs in a manner that accounts for the interactive nature of these programs, and (2) assign the development of any type of program element to the various factions of the agency that will be involved in this development in a manner that efficiently uses all the resources available to the agency. Finally, it is recommended that NASA thoroughly review any organizational structure that the agency considers adopting to insure that the structure is complete and consistent. A collection of isolated solutions to the individual problems encountered as NASA takes on the challenges of the future will not be sufficient to see it through the development and operation of the large-scale, highly interactive kinds of programs for which it will be responsible as we move into the next century.

THE "PROVINCE" AND "HERITAGE" OF MANKIND RECONSIDERED: A NEW BEGINNING

J. I. Gabrynowicz

Department of Space Studies
Center for Aerospace Sciences
University of North Dakota
Grand Forks ND 58202-7306

"The central problem of our time—one that is shared by all races and nationalities—is to discover the things, the qualities, and interests that people have in common so that durable institutions can be designed for mankind's survival."

—Justice William O. Douglas

INTRODUCTION

Despite the international agreement that accompanied the inception of the Outer Space Treaty, in the decades since its appearance in international law, factions within some nations have sought to eviscerate the progressive, peaceful, and painstakingly developed concepts it contains. Both the spirit and meaning of the Treaty have been attacked through contending interpretations advanced by international lawyers, politicians, and businesspeople. Many of the interpretations are, ultimately, premised on the erroneous belief that the infinity of space and its resources cannot provide for all Earth's people in peace. At its very core, there can be no other reason for the sophisticated and complicated maneuvering occurring among the nations. Yet this belief is, by nature, a short-term one as it results from limited access to space. Increased access will decrease fear of insufficiency and thus the perceived need to fight for resources. The time has come to reconsider where a course of action, based upon an inaccurate perception of space, is leading.

The "common heritage of mankind" and the "province of all mankind" are different legal concepts developed in international space law during the last quarter of a century. The term "province of all mankind" appears in Article 1 of the 1967 Treaty on Principles Governing the Activities of Stages in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies (Outer Space Treaty) that established the primary basis for the legal order of space. The term "common heritage of all mankind" is contained in Article 11 of the 1979 Treaty on Principles Governing Activities on the Moon and Other Celestial Bodies (Moon Treaty) and the Law of the Sea Convention (Sea Treaty).

Since the initial appearance of these provisions in international law, controversy has arisen regarding their intent and meaning as applied to a nation's right to explore and use a common environment such as space or the high seas and a nation's obligation to share benefits derived from those environments with the rest of the world. As can be expected, different interpretations are currently competing for acceptance. This is so, in part, because, in the case of the Outer Space Treaty, although a general principle was articulated, rules for acceptance and application of the principles were not. In the case of the Moon and Sea Treaties, although an effort has been made to clarify both meaning and application, the articulations are still too vague for legal certainty.

Rather than detail the legal merits and deficiencies of all competing interpretations of the two provisions, this paper will focus on the fact that these concepts are already currently available tools for the advancement of both global and U.S. interests but, because of the labyrinthine legal arguments that have been generated and some assumptions being held, they are in danger of being lost as such tools. The tendency of many observers in the U.S. to confuse the concepts of "province of all mankind" and "common heritage of mankind" and to assume that both are incompatible with U.S. commercial space interests will also be addressed. It is suggested that reconsidering these provisions can yield positions compatible with U.S. interests and that it can and should actively seek the use of these provisions as a basis for global cooperation and commercial benefit.

THE PROVINCE OF ALL MANKIND AND THE COMMON HERITAGE OF MANKIND

In negotiating the Outer Space Treaty, both the U.S. and the U.S.S.R. put forward proposals that contained similar basic concepts. The final draft of Article 1, paragraph 1 of the treaty adopted almost exactly the language of the 1966 Soviet draft (*Christol,* 1982). It provides, "The exploration and use of outer space, including the moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the *province of all mankind*" (*Outer Space Treaty,* 1967; emphasis added).

It was not until the negotiations of the Sea Treaty were underway that the term "common heritage of mankind" was used. Later, it was included in Article 1, paragraph 1 of the Moon Treaty, which reads, "The moon and its natural resources are the *common heritage of mankind,* which finds expression in the provisions of this Agreement, in particular in paragraph 5 of this article" (*Moon Treaty,* 1979; emphasis added).

A cursory look at the history of these two phrases shows a divergence in interpretation from three main quarters: the U.S., the U.S.S.R., and the collection of nations known generally as the Less Developed Countries (LDCs). By the time negotiations for the Moon Treaty had gained momentum, the U.S. generally understood "common heritage of mankind" and "the province of all mankind" to be indistinguishable and, as such, they were considered an expansion of the international legal principle of *res communis,* which traditionally meant that the *res,* the thing involved, may not become the subject of appropriation by states (*Robinson and White,* 1986, p. 187). The U.S.S.R. never accepted the common heritage concept, objecting to its roots in bourgeois Roman Law (*Dekanozov,* 1974), and later came to distinguish between it and the "province of all mankind" concept (*Maiorsky,* 1986). The LDCs collectively evolved the opinion that since most international law developed prior to their attaining nationhood status, they were not generally bound by its tenets (*Robinson and White,* 1986, p. 187). Thus, they argued, although they accepted the Charter of the United Nations, they were free to define international law as it applied to them. When it came to defining the "province of all mankind" principle, it meant all nations had vested rights in common resources and should be shared equitably among them (*Robinson and White,* 1986, p. 188). In the Law of the Sea negotiations, therefore, the LDCs led the move away from "the province of all mankind" provision as contained in the Outer Space Treaty and toward "the common heritage of mankind" provision that was later incorporated into the Moon Treaty.

This frenetic environment has given rise to volumes of competing definitions, arguments, and positions regarding the legal ramifications of the mankind provisions, the Outer Space, Sea, and Moon Treaties—all to varying degrees of vagueness. As one commentator has observed, "given the poor and inadequate substance of the generalized formulas used in space law, their interpretations have largely been attributed to individual States... [I]n the field of international law, space law has been largely conceived as international 'Softlaw'" (*Bueckling,* 1979). The practical result of this has been the failure to articulate, internationally, the legal substance of these subjects. The chaotic state of international space law does, however, provide a void that, if implanted with the seed of a transformational idea, can become pregnant with possibility.

OF LAW, POLITICS, AND THE MANKIND PROVISIONS

Supporting the concerns of the spacefaring nations, it is true that there is much in the legal history of both the Moon and Sea Treaties to advance the more restrictive "common heritage of mankind" provision that could inhibit the use and exploration of space by nations and private entities with the ability to do so. At the same time, supporting the concerns of the nonspacefaring nations, it is equally true that the same history could yield support for what they see as unreasonable exploitation. These and other positions are amply argued in the legal literature (*Cocca,* 1986). Some of the world's finest legal minds, prompted by everything from fear and promise of profit to scholarship, high purpose, and humanitarianism, have struggled with the intent and meaning of the mankind provisions for nearly three decades. Yet the controversial provisions are still in dire need of specific applications (*Panel Session,* 1982). The law, absent political will, can go no further.

The definition and application of the "province of all mankind" and "common heritage of mankind" provisions are now primarily a political problem and are, therefore, only subject to a political solution. Without supportive political action to develop the law of space, space lawyers are reduced to the twentieth century version of arguing the number of angels that can sit on the head of a pin.

Politicians and citizens must claim responsibility and work with the lawyers to develop the mankind provisions. The necessity of uniting law and politics, along with "philosophy and morality" was identified long before the current controversy over the mankind provisions (*Gorove,* 1972, p. 402).

A STRATEGIC DISTINCTION

That the "province of all mankind" provision of the Outer Space Treaty is declaratory in nature and not a specific legal maxim is well supported in the legal literature. The Outer Space Treaty "was intended to be an ideological charter for the Space Age. Readings of the debates, resolutions, and ratifying documents surrounding the Outer Space Treaty confirm its quasi-constitutional function. It was to create a set of fundamental principles that should be adhered to in all subsequent agreements and treaties" (*Robinson and White,* 1986, p. 181). In the controversies subsequent to the formulation of the fundamental principles, the legal accuracy required for their application went "off-course on the ocean of facts" (*Buecking,* 1979, p. 17) with each nation or group of nations steering its own independent course in a different direction, until those courses have become seemingly irreconcilable. However, much of what is seemingly irreconcilable lies in the continuing confusion between the "province of all mankind" and the "common heritage of mankind."

Yet a strategic distinction does exist between the two concepts. Specifically, it is that the "province of all mankind" provision contained in the Outer Space Treaty refers to "activities (exploration and use)" and that the "common heritage" provision as contained in the Moon Treaty refers to "material objects"—i.e., the former relates to, but is not the same as, the latter (*Maiorsky,* 1986).

Additional support for such a distinction recently emerged from the U.S. In a Directive on National Space Policy issued 11 February 1988, the Reagan Administration, while not claiming property rights in space materials, did announce that "The United States considers the space systems of any nation to be national property." "Systems" and "activities" are analogous in that they both suggest a productive dynamic in which materials are a component. As such, the component contributes to the overall value of the activity or system, but if isolated and/or unattainable, its inherent value substantially decreases, if it exists at all.

BUILDING UPON THE DISTINCTION

Let us consider the political possibilities that this legal distinction creates. A major objection to the Outer Space Treaty that currently exists in the U.S. arises from the general belief that its "province of all mankind" provision inhibits private enterprise because it interferes with an individual or corporate entrepreneur's right to profit from the fruits of his or her labor in space. "Fruits" are generally considered to be resources such as mined ore, manufactured water, etc. However, "the common heritage of mankind" provision does not appear in The Outer Space Treaty—only the "province of all mankind" provision does. Therefore,

applying the distinction between "activities" and "materials" along with Article 6 of the Outer Space Treaty, which allows nongovernmental entities to participate in space "activities," would enable the U.S. space community to support the Treaty without relinquishing its conviction that private enterprise in space ought to be profitable by exercising control over its processed space materials.

Supporting the "materials-activities" distinction would render clearer support for the Outer Space Treaty. Thus two of the major spacefaring nations, the U.S. and the U.S.S.R., would be able to work toward establishing a clear legal order in space. The history of space law is filled with evidence of the great progress made when these two giants move in unison. A position advocating that "the province of all mankind" relates to space activities is, in fact, supported by the customs of both the U.S. and U.S.S.R. space programs in which non-nationals have already participated on a regular and extensive basis.

The current legal status of the three treaties in which the controversial provisions are included makes it possible for the U.S. and the U.S.S.R. to join in strengthening the Outer Space Treaty. As of March 1987, the Outer Space Treaty has been ratified by 86 states, including the U.S. and U.S.S.R., and signed by 91. The Sea Treaty has 30 of the 60 ratifications needed to bring it into force, while the Moon Treaty, which, by its own terms, entered into force on 11 July 1985, has been signed by only 11 nations and ratified by 7. This tally demonstrates the opportunity to build upon the declaratory nature of the "province of all mankind" provision as contained in the Outer Space Treaty in order to establish its meaning and application before it is further confused with either the Sea Treaty or the Moon Treaty.

The Sea Treaty does not have the necessary number of ratifications at present and therefore simply is not yet in legal competition with the Outer Space Treaty. The Moon Treaty, while it may have entered into force by its own terms, also, by its own terms, severely limits the "common heritage of mankind" concept to that single document (Article 11, paragraphs 1 and 5) and to the states that are party to it (Article 11, paragraph 7b). Further, also by its own terms, the Moon Treaty leaves the determination of the application of the common heritage provision to a future regime that is not to be established until "exploitation is to become feasible" (Article 11, paragraph 5). The Treaty itself and its applications are not subject to a review conference until 5 to 10 years after the treaty enters into force (Article 18).

This leaves a stretch of time in which the U.S. and the U.S.S.R., acting upon the authority of the Outer Space Treaty, can work together to establish, with legal certainty, the meaning and application of the "province of all mankind" provision. This effort would be particularly productive because the Outer Space Treaty has an unusual character in international law. That is, it is the foundation of an interrelated "framework for a number of limited accords between individual countries and intergovernmental organizations, as well as for several subsequent treaties" (*Robinson and White,* 1986, p. 182). Therefore, if the provision of the Outer Space Treaty were to achieve legal specificity, it is reasonable to accept that the specificity should be incorporated into the framework already built upon the treaty itself, thus bringing uniformity to the entire body of international space law.

THE LDCs

A political effort by the U.S. and the U.S.S.R. to establish the legal accuracy of the "province of all mankind" provision based on its declaratory nature in the Outer Space Treaty must be carried out in absolute good faith toward the LDCs. The intensity of the conflict between spacefaring and nonspacefaring nations—developed and developing nations—regarding the interpretation of the "province" and "heritage" provisions demonstrates that they all want to be able to share in space development, and generally for the same reasons. Rather than the unaligned views of these provisions presenting insuperable obstacles to profitable space development, they in fact point to the probability that, if properly facilitated within a supportive structure, cooperation and compromise can occur.

That the LDCs have found it necessary to band together regarding the interpretation of these provisions stands as frank testimony of their fear of having their own national interests trampled in a frantic race between the U.S. and the U.S.S.R. to recklessly exploit space and the seas. For the U.S. and the U.S.S.R. to come together, in any agreement, to advance the international body of space law at the expense of the LDCs is as unproductive as not coming together at all.

That would shatter the reality that it is in the interests of currently nonspacefaring nations to support nations that do have the capability. To unfairly compromise the interests of the nations most able to go into space compromises the return of any of its benefits for everyone.

Conversely, it is not in the interest of the spacefaring nations to wantonly exploit space without regard for the needs and desires of the other nations with which they share Earth. Like mighty oaks that refuse to flex with changing winds, strong spacefaring nations can also become isolated and break.

The "activities" and "materials" distinction can lift LDCs from the theoretical bog in which the various arguments are currently mired and provide immediate results. The legal accuracy the distinction provides would enable them to free their creative energy to build on what is, rather than squander it on what might be. The "activities" and "materials" distinction provides a natural rational to advance real and current activities like Intelsat, the International Young Astronauts Program, Project Share, the Ireland-Jordan exchange for training water management workers, and the exchange of medical lectures between the U.S. and African nations (*Levin,* 1982). A plan implemented to dramatically increase the number and quality of these kinds of endeavors can quickly bring the interests of spacefaring nations and nonspacefaring nations closer together.

Neither the Sea nor the Moon Treaties has been accepted to the great degree with which the Outer Space Treaty has. The truth is that the "common heritage of mankind" concept is in a legal limbo—a limbo that is further extended by the Moon Treaty's deferral of the application of the concept until resource exploitation becomes "feasible."

Whatever else may be unclear about the application of the "province" or "heritage" of mankind provisions, one thing is abundantly clear: without access to celestial resources, its exploitation will never be "feasible." Further, of what value is lunar ore? None, unless an economically viable, systematic activity is in place to obtain it.

For the vast majority of developing states, national means of space access is simply impossible. Accepting the "activities-materials" distinction would give these nations immediate participation in what is feasible now. While doing so, they gain access to political decisions that give force to legal principles, now and in the future. Additionally, the distinction makes it unnecessary for any nation to change its ratification decisions as they

pertain to the more controversial Moon Treaty. Without having to change their current positions, the LDCs could be active partners in the negotiations and determinations that would be necessary in implementing shared activities and which could ripen into a wider understanding and acceptance of the goals of the Moon Treaty. And, as activities develop, it will become necessary to find ways to share the materials inherently necessary to that development for the sake of the ongoing success of the activities.

THE U.S., COMMERCIALIZATION, THE MANKIND PROVISIONS, AND THE OUTER SPACE TREATY

Considering a new strategic opportunity is, of course, an invitation to the U.S. to reconsider its current position. In the fray over the mankind provisions, U.S. observers have generally adopted the view that they stand as an obstacle to the advancement of the interests of the U.S. in space and should be, if not abandoned, justifiably ignored. This is so, according to this view, because of the fear that treaty provisions exclude private commercial enterprise and can force distribution of space resources among all nations with little regard to the investment made by the nation or organization that actually obtained them. The tragedy is that evading the mankind provisions because of this definition supports and gives credence to the very ideology that the position is intended to resist.

Disavowal of the mankind provisions on the grounds that they are anti-commercial and anti-free enterprise is tacit acceptance that they are anti-commercial and anti-free enterprise. Tacitly accepting that the mankind provisions inhibit free enterprise has an undesirable fourfold effect for the U.S. First, it helps create a self-fulfilling prophecy in which the successful formal adoption of the anti-commercial meaning becomes more likely. Second, failing to establish a pro-commercial definition of the mankind provisions makes it more difficult for nations that are currently taking anti-commercial positions to change their positions if they were to come to believe it would be in their interest to do so. Third, failing to take a stand is reactionary and therefore inherently less powerful than making a choice to create a definition. Fourth, not taking a stand is contrary to the U.S.'s historical commitment to the pursuit of freedom.

There are alternatives to tacitly accepting that the mankind provisions stand for less than freedom to responsibly develop the space environment. At one end of the spectrum political options exist. Without a domestic political drive to establish the meaning and application of the provisions, fertile ground for nurturing international support, cooperation, and real growth of space development—public and private—would be given up. Abandoning the mankind provisions is also contrary to the view of the National Commission on Space, which states "that the existing United Nations treaties that [the United States has] ratified provide a sufficient legal framework for the future uses of space." A vigorous, intentional, and openly visible policy of utilizing the best of nearly three decades of precedent to maintain a free enterprise meaning of the mankind provisions can be declared and pursued by the U.S. Doing this, the U.S. would be building on its early active, pro-commercial history in the adoption of the Outer Space Treaty.

The original intention behind the "province of all mankind" provision in the Outer Space Treaty was to create a new regime for its application. This provides the U.S. with an alternative to its current experience of being unable to advance its own interests and those of space development in general because of the "politicization and bureaucratization" (*NCOS*, 1986) of the United Nations bodies that are responsible for formulating space policy. On the authority of the Outer Space Treaty, the U.S. could join the U.S.S.R. in its 1985 call to create a new international space law organization and thus create anew what has become rigid in the old.

At the other end of the spectrum legal options exist. Chief among the treaties that the National Commission on Space considers as providing a sufficient legal framework for the future uses of space is the Outer Space Treaty. In its ratification process, the U.S. simultaneously issued a legal opinion of the State Department (*Christol*, 1982, pp. 42-43) and an understanding by the Senate (*Christol*, 1982, p. 43) respecting the meaning and application of the "province of all mankind" provision. Also, along with Ambassador Goldberg's testimony (*McDougall*, 1985, p. 418), the U.S. is on record as recognizing that the mankind provisions of the Treaty are compatible with conducting and developing free space enterprise and the right to determine how it shares the benefits and results of U.S. space activities. The U.S. further strengthened this pro-commercial interpretation in its 1977 response to the 1976 Bogota Declaration (*Christol*, 1982, p. 40). In short, there are ways the U.S. can take a bold stand for both the private and public commercial meaning of the mankind provisions without resorting to unilateral actions or impairing its own values.

A particular brand of reaction to the mankind provisions requires special note. Within the U.S. space community there are factions that would have the 1967 Outer Space Treaty declared unconstitutional. It is clear that this position is being taken out of frustration and anger over the feeble condition of the U.S. space program and the tragedies it has suffered.

The proponents of this position must be reminded that Article 6 of the U.S. Constitution raises a properly ratified treaty to the supreme law of the land. Extreme care and thought must be applied to this particular consideration. Current U.S. history has demonstrated that even high officials, sworn to uphold the Constitution, were able to, and did, rationalize breaking their oaths, abandoning their duty, and violating the Constitution for their own purposes. The danger of reneging on a properly ratified treaty is the further erosion of popular respect for the Constitution that can only imperil domestic well-being. History has shown that lack of respect for the rule of law is the first step to national disintegraton.

Internationally, it is not to be forgotten, either, that were the U.S. to renege on its original ratification of the Outer Space Treaty, formally or informally, it would send a signal to other nations to also treat their ratifications in self-serving ways—ways that, collectively, would create an environment of lawless uncertainty, the worst environment for the megaprojects that space development requires. It is a hard fact that for the U.S. to get what it wants in space, it must keep its word on Earth.

Additionally, the apparent shifts in the U.S.S.R. portend a possible transformation of the relationship between the U.S.S.R., the U.S., and other nations. Much skepticism exists as to the nature and sincerity of the changes. Mikhail Gorbachev has asked the West to assist the U.S.S.R. in making a transition to a more modern commercial power and to help it move away from a military economy toward a civilian economy. Working with the U.S. within the Outer Space Treaty will meet Gorbachev's plea for assistance,

challenge the U.S.S.R. to demonstrate its sincerity, and place the U.S. at the forefront of innovative peace initiatives in the world community.

Finally, and most importantly for the U.S., is that beneath the words of treaties, commercial interests, political plans, and national positions lies a contest of ideas. One of the competing ideas is that people can live free and prosper with integrity. This idea has been held by the people of the U.S. for over two centuries. It is an important idea. Taking a stand to advance the mankind provisions and making a commitment to their practical applications will insure that the idea thrives. And where this idea thrives, so do we. It is time for the U.S. to get on with the business of the mankind provisions—a business that was begun by it, bears its stamp, and could lead to a new beginning for a world in crisis.

CONCLUSION

When, through human industry, a small, round, metal object obtained a stable orbit above Earth, the mankind provisions emerged from the communal mind in a moment of principle-seeking clarity, as it perceived that humanity had made its first thrust beyond Earth and nothing would ever be the same again. The provisions simply say that humanity must move on as one, or it will not be able to move. They recognize the practical requirements of profound change.

The mankind provisions within the development of space encompass the most important questions of modern times. They demand new thinking about strangling historical precedents regarding resources, technology, and arms. The conflict that surrounds the mankind provisions, if met with integrity and the political will to compromise, presents an unparalleled opportunity for positive advancement in world affairs. The mankind provisions provide a perspective that requires all nations to honestly consider how their positions have contributed to the progressive breakdown of what was once one of the most promising paths to peaceful, productive coexistence both on Earth and in space. This must be followed by unconditional national commitments to find and follow that path again.

REFERENCES

Bueckling A. (1979) The strategy of semantics and the mankind provisions of the Space Treaty. *J. Space L., 7,* 15-22.

Christol C. Q. (1982) *The Modern International Law of Outer Space,* p. 38. Pergamon, New York.

Cocca A. A. (1986) The common heritage of mankind: Doctrine and principle of space law—An overview. *Proceedings of the Twenty-Ninth Colloquium on the Law of Outer Space,* p. 17. AIAA, New York.

Dekanozov R. V. (1974) Juridical nature of outer space, including the Moon and other celestial bodies. *Proceedings of the Seventeenth Colloquium on the Law of Outer Space,* pp. 200-201. AIAA, New York.

Gorove S. (1972) The concept of the common heritage of mankind: A political, moral or legal innovation? *San Diego L. R., 9,* 390-403.

Levin L. (1982) Foreign and domestic U.S. policies—Spectrum reservations and media balance. *Telecommunications Policy, 6,* 123.

Maiorsky B. (1986) A few reflections on the meaning and the interrelation of "province of all mankind" and "common heritage of mankind" notions. *Proceedings of the Twenty-Ninth Colloquium on the Law of Outer Space,* pp. 58-59. AIAA, New York.

McDougall W. A. (1985) ... *the Heavens and the Earth—A Political History of the Space Age,* p. 418. Basic Books, New York.

Moon Treaty (Agreement Governing the Activities of States on the Moon and Other Celestial Bodies) (1979) U.N. GAOR, 34th Sess., Supp. No. 20 (Doc. A/34/20).

NCOS (National Commission on Space) (1986) *Pioneering the Space Frontier: The Report of the National Commission on Space,* p. 166. Bantam Books, New York.

Outer Space Treaty (Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies) (1967) 18 U.S.T. 2410, T.I.A.S.6347, 610 U.N.T.S. 205 (January 1967, effective October 10, 1967).

Panel Session (1982) Outer space, international law, international regimes and the common heritage of mankind. *J. Space L., 10,* 65-69.

Robinson G. S. and White H. M. Jr. (1986) *Envoys of Mankind—A Declaration of First Principles for the Governance of Space Societies,* p. 187. Smithsonian Institution, Washington, DC.

A BASIS OF SETTLEMENT: ECONOMIC FOUNDATIONS OF PERMANENT PIONEER COMMUNITIES

N93-14019

Eric M. Jones

Earth and Space Science Division
Los Alamos National Laboratory
Los Alamos NM 87545

High transport costs will dominate the course of lunar development. During the earliest phases, when lunar facilities consist of a research and resource development complex with staff serving tours of a few months, transport costs will encourage local production of fuel, food, and building materials. Once these capabilities are in place and the number of personnel grows to a few hundred, staff rotation might well dominate transport budgets. At that point it would make economic sense to encourage some members of staff to become permanent residents. By analogy with early British settlement in Australia, a vigorous private sector economy could emerge if the lunar organization provided quasi-export earnings through its role as the community's major employer and as the major buyer of locally produced goods. By providing such a market for goods and services, the lunar organization would not only provide a means whereby permanent residents could support themselves, but could also accelerate the process of replacing imported goods with local manufactures, thereby reducing the cost of operations. By analogy with recent Alaskan experience, if the resource development activity started making money from sales to orbital customers, export taxes and/or royalty payments could also provide means by which a lunar community could support itself.

INTRODUCTION

In the half century before Sputnik, many space enthusiasts believed that space travel would eventually lead to settlement; that permanent residents of extraterrestrial communities would someday raise children and make livings from mining, manufacturing, tourism, farming, and a hundred other occupations, as had countless terrestrial settlers before them (e.g., *Clarke,* 1950). The settlement goal has remained in the background since Sputnik; the space powers have concentrated on transportation technologies and space science. However, posterity may well remember these efforts as preliminaries to settlement. In some sense, for the last quarter century human and robot explorers have been doing basic reconnaissance, and while there is a good deal of exploring still left to do, the time for space pioneering may be only a few decades in the future. Implementation of the goal of "expanding the human presence beyond Earth into the solar system," adopted recently by the Reagan Administration, could lead, step-by-step, from an Antarctic-style science base to permanent settlement.

Setting a goal is, of course, a different matter from actually accomplishing the deed. In the last few years we have made great progress in sketching the essential features of the science bases and resource development facilities that will be important precursors to permanent settlements (*Mendell,* 1985). With those sketches in hand, we can now give thought to ways in which economically viable extraterrestrial communities might plausibly emerge in the context of an affordable space program.

Although pioneering settlements, particularly in novel environments, are often established for political, ideological, historical, or social reasons, their long-term viability and growth almost always depend on economic factors. Living standards and the potential for economic growth depend, in part, on the development of local production capacity. However, any small community—pioneering or otherwise—can produce only some of the needed goods and services. The rest have to be bought from outside suppliers. Support of an import capacity comes from sales to customers outside the community. Export opportunities available to early-stage lunar or martian communities will be limited; the emergence of permanent communities will require dependence on public sector employment and on public sector markets to a degree uncommon in American frontier experience, in particular, and in terrestrial frontier experience in general.

THE CLASSIC AMERICAN PATTERN

Because of our particular national experience, Americans are generally used to thinking about the frontier in terms of small-scale, private settlement ventures. The vast majority of American settlers were family farmers, farm workers, trappers, miners, or town-based craftsmen and professionals, almost all of whom were either self-employed or worked for others in small-scale operations (*Billington,* 1963; *Merck,* 1978). In circumstances where capital requirements and economies of scale favored or mandated large enterprises like the cash-crop plantations of the Old South, these too were private ventures. Although the states and the federal government played vital roles in support of private ventures—exploring new territory and providing surveys, Army protection, direct and indirect subsidies of the construction and operation of canals and railroads, etc.—most settlers supported themselves in the private sector economy. Typical American pioneers sought farmland not too far removed from river, road, or railroad. Their goal was to produce, as soon as possible, food surpluses that could be sold to the Eastern cities and even to Europe in exchange for the goods they could not produce locally. Although retained Calvanist/English attitudes toward central authority and land ownership were important factors in deter-

mining the dominant pattern of American settlement, above all it was the abundance of good farmland and the accessibility of large markets that shaped the American experience. Good land and low-cost transport allowed individual farmers, even at mid-continent, a considerable share in the fruits of the industrial age. By and large, settlers provided their own import capacity through their individual ability to directly produce exportable goods. Not all settlement ventures have had a comparable means of support.

ALASKAN SETTLEMENT

The history of Alaska illustrates an alternative pattern of development. The territory's early nonaboriginal settlement episodes resulted from the fur trade and from a series of gold and copper discoveries. However, unlike California, Alaska had no agricultural potential to take up the slack when the gold began to run out (*National Resources Committee,* 1937). For a variety of social, economic, and legal reasons, even salmon—a renewable fixed-based resource that had been the basis of aboriginal settlement—has played only a limited role in subsequent Alaskan development. Taxes on salmon production provided the majority of revenues available to the Territory of Alaska—72% in 1940 (*Cooley,* 1966)—but, since the industry employed a nonresident, seasonal workforce, it provided little basis for permanent settlement. Other than those towns that owed their origins directly or indirectly to mining, almost all Alaskan settlement has resulted from public expenditures of one form or another. The city of Anchorage, for instance, started as a construction camp for a government railroad built for the express purpose of encouraging settlement. However, because of the lack of agricultural potential and other factors, it was the railroad itself, via salaries and other expenditures, that provided the economic support for Anchorage and a handful of other towns along the route (*Wilson,* 1977). Before 1940, Alaska's nonaboriginal population never exceeded 30,000. Among Alaskan boosters, this state of affairs was often attributed to Federal "neglect," but was more a consequence of local economic realities.

However, beginning in 1940, population and import capacity began to increase dramatically because of military construction and other government activities that came with World War II and the Cold War (*Rogers,* 1962). In essence, Alaska began to make a living by providing government service, particularly service to the national defense effort. Further expansion, beginning in the 1960s, resulted from oil discoveries, related construction activities, and, particularly, from oil revenues that poured into the Alaskan treasury. As part of statehood legislation, Alaska acquired ownership of potential oil lands at Prudhoe Bay and, after oil was actually discovered, began to reap enormous revenues. Although Alaska invests (mostly out of state) a significant fraction of its oil earnings in a Permanent Fund—a pool of money that might, at some future date, provide support for some public-sector activities should earnings for nonrenewable resources dry up—most oil revenues are spent on government salaries, public works, and even a Permanent Fund dividend paid annually to every year-round resident. Oil revenues ultimately pay for about 80% of Alaska's imports, and fuel most of the local economy.

For a variety of reasons, Alaska has yet to develop any alternative means of paying for imports and, indeed, there is very little local manufacturing of any kind. Since 1940, a combination of relatively inexpensive imports and a very high wage scale have made it impossible for locally produced goods to compete. Alaska's internal economy depends almost entirely on the service sector. Incentives toward local production of goods have been weak or nonexistent.

The circumstances of lunar settlement will differ in obvious ways from both the classic American and recent Alaskan experiences. In particular, while a very high cost of transport will severely restrict the range of economic options—for instance, making it virtually impossible for individual settlers to make a living as private exporters—those same high costs will put a premium on local production capacity. This combination of circumstances bears close resemblance to the early settlement of Australia, an important historical case that suggests how growth of a private sector economy might be stimulated in the lunar or martian case.

THE AUSTRALIAN ANALOG

Before the advent of clipperships and steam, the only products that could compete in global markets were those with very high value per unit weight. Examples included precious metals and gems, silk and certain other manufactured goods, spices, and drugs like tea, rum, and tobacco. Grain and other ordinary foodstuffs could bear the cost of transport across the North Atlantic, but certainly couldn't be shipped profitably to Europe from as far away as Australia (*Blainey,* 1966).

Cursory examination of the Australian coasts during the seventeenth and eighteenth centuries had revealed no obvious products of value in international trade. Even after Captain Cook noted the relative fertility of the southeast coast, there wasn't much British interest in Australian settlement for the two simple reasons that (1) private settlers could find easier outlets for their energies in the United States and Canada, and (2) His Majesty's government was preoccuppied with the American Revolution and ongoing European conflicts. Australia would certainly have been settled eventually, but probably not until well into the nineteenth century had not other events intervened.

The roots of Australian settlement are to be found in the British practice of sending convicts to the American colonies. Although the number of convicts comprised only a tiny fraction of total eighteenth century immigration into the Americas, a refusal by the colonies to accept any more convicts after 1774 created serious problems for the British government. By the mid-1780s Britain's local jails and the country's few prisons were becoming very overcrowded. The government was under considerable public pressure to devise a solution but had a difficult time finding one it thought it could afford. Finally, in 1786, the Pitt government decided to establish a penal settlement in Australia (*Mackay,* 1985). Although no one of that time would have described the venture in the following way, we might say that His Majesty's government decided that an Australian settlement could earn its keep by providing a public service, namely operating a prison. The First Fleet arrived at Sydney Cove in January 1788. On board the 11 ships were about 1000 people: 750 of them convicts, and the rest government employees and their families.

Planners in London had assumed that the convicts would grow on government farms all the food that the colony would need. As it turned out, the government farms were never very productive. Fortunately, within a few years, some of the employees and a few ex-convicts were producing surpluses on private farms. The penal establishment, which typically was responsible for feeding about half the population at any one time, began buying

food in quantity and at prices less than those of imports (*Fletcher,* 1976a). These purchases by government, together with salaries paid to its employees, provided hard cash with which the private sector could satisfy its import needs.

Because of the great distance from Europe, imports were always expensive, and there was plenty of incentive to produce goods and services locally. For a quarter century, development of the private sector was fueled both by growth of the population and by the need to replace imports. Agriculture was the first priority, but most people in the colony had neither the skills nor the opportunity to make a living from farming. Indeed, farming required at most about one third of the labor force, convict or otherwise. Had everyone been a farmer, the colony would not have prospered as it did, since there would have literally been no markets for two thirds of the potential output. However, the colony was blessed with a labor force that, although burdened with a disproportionate number of unskilled people, otherwise represented a fair cross section of the contemporary British talent pool. There were craftsmen of almost every description, along with clerks, tradesmen, and assorted professionals. Some were ex-convicts, some were convicts given permission to support themselves (thereby reducing the penal establishment's costs), and these were eventually joined by people born in the colony (*Shaw,* 1969). In one way or another most of these people helped diversify and strengthen the local economy.

At any one time, the colonial population could be divided roughly into three groups. One group consisted of the people entirely supported—fed, clothed, and housed—by the penal establishment. As mentioned previously, for many years this included about half the population. Although the colony had no viable export, government expenditures to feed these people and otherwise support the penal establishment provided the private sector with the essential hard cash with which it could pay for imports. Government monies entered the colonial economy in the form of salaries and of payment for goods bought by the Commissariat. The second segment of the population comprised those people to whom these monies were paid. It was a relatively small group, mostly civil and military officers who were joined later by a number of ex-convicts who prospered in the colony. This group played a central role in the economy through access to and control of the colony's supply of hard cash (*Butlin,* 1985). The officers could have used the cash solely to support themselves with imports, but that would have been an inefficient use of the cash resource. Many of them had come to the colony intending to get rich, so they bought less expensive, locally produced goods and services from the remaining segment of the population, those people without direct economic connection with the penal establishment. These local purchases freed capital for investment in enterprises that would yield additional hard cash through sales of meat and grain to the penal establishment; many of the officers did very well for themselves but, by spending money locally, they helped stimulate and diversify the economy. Finally, as the nonconvict population grew, those people without direct access to hard cash nonetheless had considerable dealings with each other. Through the process of import replacement, the economic impact of government expenditures was greatly increased; by the 1820s the gross domestic product had increased to about four or five times the level of government expenditures and, hence, of the level of imports (*Butlin,* 1985). By early nineteenth century standards the Australian settlement enjoyed a very high standard of living.

By about 1820 the process of replacing imports had gone about as far as it could, and that presented the colonial economy with a problem. Government expenditures within the colony per convict were leveling off while at the same time the proportion of ex-convicts and native-born adults was increasing. In essence, the import capacity—wholly supported at the time by government expenditures—was being diluted. The economic importance of the penal establishment was about to go into decline and with it the standard of living—unless an export could be found. High transport costs limited the options, but sheep breeders gradually discovered that they could make money from wool exports (*Abbott,* 1969; *Fletcher,* 1976a).

The pastoral industry had arisen because of the potential for large cash earnings from meat sales to the Commissariat. Although the colony became more or less self-sufficient in grain by the end of the 1700s and produced large amounts of pork and chicken, the numbers of cattle and sheep increased very slowly. For nearly three decades the colony imported significant quantities of meat. Indeed, the Commissariat bought no beef or mutton during the colony's first 20 years because the early governors wanted to ensure that the herds and flocks would grow as quickly as possible. However, it was obvious that the Commissariat would start buying meat in quantity once the animal populations had grown large enough that demand could be satisfied out of natural increase. Once the government started buying meat, the level of expenditures in the colony would increase significantly. In anticipation of such sales, a number of the civil and military officers concentrated their private efforts on the development of pastoral operations. As with grain production, they were much more successful in raising animals than was the government. Commissariat meat purchases began in 1808 and sustained expansion of the pastoral industry until the mid-1820s, by which time local supply was satisfying demand.

The colony's first Merino sheep, a Spanish breed developed for wool production, had been introduced into Australia in the 1790s but, because of the anticipated government demand for meat, little effort had been devoted to breeding animals for fleece quality rather than carcass weight. However, as meat supplies caught up with demand, meat prices began to decline relative to wool. This, together with other factors, led to a rapid expansion of the Merino flocks in the 1820s and 1830s. By the end of the 1830s, New South Wales was earning enough from wool exports to end its dependance on the penal establishment; and in 1842 the colony successfully lobbied London to stop sending convicts (*Fletcher,* 1976b).

LUNAR SETTLEMENT

It is extremely unlikely that there will be a lunar penal establishment any time soon—the economics are all wrong, among other things. However, a lunar research/resource development organization could play much the same economic role that the penal establishment did in New South Wales. The only significant difference would be the fact that, unlike the Australian settlement, in the beginning a lunar facility would have no permanent residents.

We will begin with a base camp. No matter whether we commit to a lunar development program for scientific, geopolitical, or other reasons, the very high cost of transport will put a premium on the development of local production capabilities. Let us assume, for the sake of discussion, that the emergent lunar-base

program will be fiscally constrained to the annual delivery to low Earth orbit (LEO) of 900 tons specifically for the support of lunar operations. This is equivalent to six Saturn V launches. Current scenarios (e.g., *Babb et al.,* 1985) suggest these additional ground rules: that staff of the lunar facility serve six-month tours; that the facility consist of about one 20-ton module and 10 tons of CELSS equipment per staff position; and that facilities to produce oxygen, heat shields, and construction material mass about 100 tons each. Within these constraints, the facility could achieve basic self-sufficiencies in the production of food, construction materials, and propellant by the end of the first decade. The facility at that point might have a staff of 30 or so.

Past this point of development, the transport budget would be dominated by deliveries of CELSS and other high-tech equipment, and by staff rotation. The staff size could gradually increase—constrained by CELSS installation—until staff rotation began to consume virtually all the transport budget. If we assume a reusable five-ton, four-passenger transfer vehicle, fueled with lunar oxygen and terrestrial hydrogen, together with a six-month duty tour, the cost of maintaining one staff position is about three tons delivered annually to LEO. The maximum staff size is then about 300.

At some point, and probably at one well short of a 300-position staff, the economics of crew rotation and training should force serious consideration of permanent residency. Much will depend, of course, on the perceived economic, geopolitical, and/or scientific/technical return generated by the lunar facility; but once the facility begins to earn its keep, at least in intangible terms, then a commitment to permanent residency on the part of the operating organization, its sponsors, and the potential residents becomes plausible. At this point lunar settlement would begin.

During the stages leading up to settlement, living and working conditions at a lunar facility will necessarily be spartan but must be acceptable to staff. The Atlantic Richfield (ARCO) facility at Prudhoe Bay offers some guidance. There, each member of the 500-person staff has a private bedroom of about 10 sq m and shares a 7-sq m bathroom with one other person. There are, in addition, about 700 sq m of common areas—cafeteria, dining rooms, lounges, atrium, gymnasium, movie theater, etc.—for a total of about 18 sq m of nonwork space per person (ARCO staff, private communication, 1987). Extensive common areas are particularly important.

Would-be permanent residents of a lunar facility would expect and demand larger living quarters, including more common areas and a higher standard of living than would be available in the precursor stages. Expansion of the physical plant would probably not be a major expense, provided that several tens of square meters per person could be built (in quantity, of course) at a cost of a few tons of material shipped to LEO. On the other hand, expanded services and access to goods could be quite expensive unless efforts were devoted toward local production. Of necessity, the process of import replacement would continue and, by analogy with the Australian case, could spur development of a local private sector.

A way in which the process could begin is illustrated by the history of Los Alamos, the research town founded during the Second World War expressly to house Manhattan Project personnel (e.g., *Lyon and Evans,* 1984). At first, people put up with some rather primitive conditions, but it was wartime, and few of them expected to stay once the conflict was over. However, after the war, when the federal government decided that the research effort would have to continue, the Atomic Energy Commission began building permanent housing and providing services that would make life attractive to the kinds of people that the laboratory needed. The AEC was never very happy about running what was, in essence, a civilian town and eventually sold all the housing and businesses to residents. It also began turning public services over to the community, a process that continues even now. The AEC, having been the town's landlord, retained only the more limited role of operating the laboratory, the town's dominant employer. The Los Alamos analogy is only partly relevant because transport costs were never a major factor; from the beginning, the town and laboratory were well integrated into the state and national economies. Other than the laboratory and the schools, the only economic activity in town has been at the retail level. Import replacement was never a major consideration. However, the Los Alamos experience suggests that, at a lunar facility, transfer of support services to residents could be a first step toward the emergence of a private sector economy.

In the early stages, the lunar facility, like the ARCO operation at Prudhoe, could be operated in a cashless mode. Salaries for rotating employees might be substantial by terrestrial standards but would have little relation to the actual cost to the organization of maintaining an individual on the lunar surface. There being no way to spend money at the lunar base, those salaries would be banked on Earth. However, once support services are transferred to residents—perhaps through lease/purchase arrangements—an important second step would be conversion of the lunar facility (at least with regard to permanent residents) to a cash-based operation. This would require payment of salaries commensurate with a lunar cost of living.

Transfer of support functions and conversion of the local economy to a cash basis would not immediately produce savings for the operating organization except in terms of reduced expenditures for staff rotation and training. Permanent residents will require a high standard of living and hence a higher level of imports than would rotating staff, at least until there is more import substitution. However, transfer of support functions and payment of salaries would provide would-be entrepreneurs with sources of capital and, in the longer term, would accelerate the import replacement process. That, in turn, would reduce the cost to the lunar organization of conducting the retained research and resource development functions.

By analogy with the Australian case, a lunar research/resource development organization may be the only means of supporting development of a local private sector economy. Both as an employer and buyer, the organization can provide quasi-export earnings with which permanent residents can pay for private imports. The organization as a buyer—for instance of goods and services to support visiting research personnel (the lunar equivalent of convicts)—would provide the major market that would probably be necessary to stimulate import replacement on a significant scale.

There is one other way in which a lunar community might support itself. Although, in the long term, the private sector may well produce a viable export, the lunar equivalent of wool, there is also a very real prospect that, at a relatively early date, the resource arm of the lunar organization (although perhaps not a martian counterpart) would begin making profits from sales to orbital customers. These export earnings would certainly generate jobs but, as the Territory of Alaska discovered during its formative years, severance (export) taxes are a far more reliable means of forcing investment in community development.

CONCLUSIONS

An appeal to historical analogs suggests that permanent settlements on the Moon or Mars can emerge from a properly structural, sustained program of research and resource development. The things needed in order to reach that goal fall into a few broad categories. These include

1. A capability of launching into low-Earth-orbit—and then on to the Moon or Mars—significant amounts of cargo on a sustained basis;

2. Engineering research that will allow production of food, fuel, and building materials from local resources at the earliest possible date;

3. A research program that will make the best possible use of the facilities and, thereby, provide a substantial scientific and engineering return on the investment in the years before there are commercial profits;

4. An administrative and legal environment conducive to settlement and the emergence of a local private sector economy; and

5. A commitment to the endeavor for long enough to give it a reasonable chance of success.

Acknowledgments. This work is the result of a sabbatical year spent at the University of Melbourne and at the University of Alaska-Anchorage. I want to thank G. Blainey, L. Robson, P. Statham, and S. Haycox for their guidance and encouragement. This work is supported by the Los Alamos National Laboratory, which is operated by the University of California for the U.S. Department of Energy.

REFERENCES

Abbott G. J. (1969) The Pastoral Industry. In *Economic Growth in Australia 1788-1821* (G. J. Abbott and N. B. Nairn, eds.), pp. 139-161. Melbourne Univ., Melbourne.

Babb G. R., Davis H. P., Phillips R. G., and Stump W. R. (1985) Impact of lunar and planetary missions on the space station. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 125-139. Lunar and Planetary Institute, Houston.

Billington R. A. (1963) *America's Frontier Heritage*. Univ. of New Mexico, Albuquerque. 310 pp.

Blainey G. (1966) *The Tyranny of Distance*. Sun, Melbourne. 365 pp.

Butlin N. G. (1985) Free Lunches Antipodean Style: NSW Economy 1788-1810. *Working Papers in Economic History No. 10*, Australian National Univ., Canberra. 55 pp.

Butlin S. J. (1953) *Foundations of the Australia Monetary System*. Melbourne Univ., Melbourne. 727 pp.

Clarke A. C. (1950) *Exploration of Space*. Harper, New York. 199 pp.

Cooley R. (1966) *Alaska: A Challenge in Conservation*. Univ. of Wisconsin, Madison. 230 pp.

Fletcher B. (1976a) *Landed Enterprise and Penal Society*. Sydney Univ., Sydney. 237 pp.

Fletcher B. (1976b) *Colonial Australia Before 1850*. Nelson, Melbourne. 212 pp.

Lyon F. and Evans J. (1984) *Los Alamos: The First Forty Years*. Los Alamos Historical Society, Los Alamos. 176 pp.

Mackay D. (1985) *A Place of Exile*. Oxford, Melbourne. 127 pp.

Mendell W. W., ed. (1985) *Lunar Bases and Space Activities of the 21st Century*. Lunar and Planetary Institute, Houston. 865 pp.

Merck F. (1978) *History of the Westward Movement*. Knopf, New York. 660 pp.

National Resources Committee (1937) *Regional Planning; Part VII: Alaska—Its Resources and Development*. U.S. Government, Washington, DC. 238 pp.

Rogers G. W. (1962) *The Future of Alaska*. Johns Hopkins, Baltimore. 311 pp.

Shaw A. G. L. (1969) Labour. In *Economic Growth of Australia 1788-1821* (G. J. Abbott and N. B. Nairn, eds.), pp. 105-118. Melbourne Univ., Melbourne.

Wilson W. H. (1977) *Railroad in the Clouds*. Pruett, Boulder. 279 pp.

THE LUNAR "COMMUNITY CHURCH": CONTRIBUTIONS TO LUNAR LIVING AND TO EVOLUTION OF ETHICAL AND SPIRITUAL THINKING

J. H. Allton

351 Lakeside Lane, #206
Houston TX 77058

Should religious institutions get interested in lunar settlement? Would their participation make positive contributions or would it discourage creative diversity and interfere with science and good technical judgement? Among the spacefaring nations of today, religion is distinctly separated from the governments that plan and pay for space exploration. However, as we move off the Earth, our art and philosophy will follow our science and technology. Spiritual thinking will follow as part of our culture. It is time to consider in what ways this can occur constructively. Transport of religious values to a lunar base may have positive effects in two ways. First, the social structure of a "community church," as found in today's United States, supports its members psychologically. Mutual psychological and social support will be needed in a lunar community. Second, our space pioneers will experience a unique view of the universe which may, in their philosophical discussions, forge new ideas in the spiritual realm.

SUPPORTIVE SOCIAL FUNCTIONS

The lunar base's physical environment is unforgiving. Every member must contribute to the success of the community. All lives depend upon each person performing well for lengthy periods. Learning to live in a lunar community means feeling at home with isolation, confinement, deprivation, and risk. Some social challenges of long-term space living suggested by *Connors et al.* (1985) include those with which the American-tradition "community of faith" have successful experience. Possibilities for positive contributions occur in these contexts:

1. *Withdrawal from the home community.* "People under normal circumstances are embedded in a complex social matrix that links them with family members, friendship groups, large-scale organizations and society." Lunar base dwellers are likely to be "separated from loved ones and friends, [with the] concomitant loss of reassurance, affection and respect that flow in such relationships" (*Connors et al.,* 1985). A lunar "community church" could provide a setting for the remembrance of spiritual roots and a sense of history. Performance of religious rituals and the celebration of religious festivals could reinforce the home link. This is an especially important link, for these roots are often associated with strength during stressful times, such as loss of a loved one. Apollo 11 astronaut Edwin Aldrin chose to celebrate Communion on the surface of the Sea of Tranquility as an extension of his home church's Communion service, recognizing the mutual spiritual support among church members. The community church has long been a reminder of family history by the recording of births, marriages, and deaths. Many faiths portray a deity with parental qualities—protecting, counseling, encouraging. These are useful psychological links to the family on Earth.

Another effect of withdrawal from the larger society is a loss in the variety of social relationships and lessened opportunity to exercise one's own social roles—teacher, daughter, student (*Connors et al.,* 1985). Participation in a community church would add another role and allow relationships to develop in a spiritual context.

2. *Social tensions in a microsociety.* Isolation and confinement impairs people's ability to get along with others. They may shun competitive activities or withdraw. Intense contact with very few people appears to magnify the effects of dissimilarities and annoying habits. Conversely, the group may ostracize an individual (*Connors et al.,* 1985). Weekly gatherings in a community church, in which focusing remarks by the group leader and "mood music" are preparatory to a period of quiet contemplation, may help annoyances to be put in proper perspective.

3. *Personal crises.* The reaction to personal crises, such as death of a family member or crewmate, could result in risk to the mission and crew. One reaction, which can be exacerbated by drugs, is heightened activity and increased hostility. One Antarctic polar resident, upon learning of the death of a family member, became drunk and destroyed property before he was subdued. Experiencing grief is essential to recovery. The strength of the grief reaction is related to the intensity of interaction. Interaction with crewmates may or may not be positive, but it is likely to be intense (*Connors et al.,* 1985). Death at a lunar base will be a traumatic event for surviving crew members. "Pastoral care" will be needed. Group training and emotional support for coping with grief, stress, illness, drug abuse, parenting, and marriage problems are ongoing programs in community churches. Further, the church is perceived by many to be a source of support in these areas.

4. *Personal mental resilience.* In prolonged isolation and confinement, many individuals, with intentions of working on creative projects, instead mark time by such activities as solitaire. Feelings of helplessness and worthlessness may occur (*Connors et al.,* 1985). One cannot mark time until "end of mission" when one truly "lives" at a lunar base. Persons participating in a com-

munity of faith would gain reinforcement in their personal beliefs concerned with purpose in life, self-worth, sense of a better future, and reliance on a strength greater than themselves in emergencies.

These are only suggestions of some ways that lunar base living may benefit from lessons learned in the American-tradition community church. Other religions may have different concepts that would also be helpful. Each suggested concept needs to be evaluated for both beneficial and detrimental aspects, and perhaps modified or even discarded. This evaluation must be done with care and caution, for historical examples of conflict between and within religious groups are numerous. Scholars should prepare to make this evaluation by defining lunar community analogs in which to study the effect of religious beliefs. The main point is that religious insitutions should get involved, for without them we may overlook some important ideas. "If large numbers of people are to spend extended periods of time isolated and confined in space, the goal must be to discover or to establish positive conditions under which psychological function and social life can prosper and flourish" (*Connors et al.,* 1985).

CONTRIBUTIONS TO ETHICAL AND SPIRITUAL THINKING

Viewing the Earth from far above its surface has affected the way some space travelers feel about world peace, pollution, relationships with other people, and God (or gods). Changes in perception of "our world" and interactions among its inhabitants, due to the visual and emotional impact of seeing the Earth from farther away, perhaps entirely in the field of view, have been termed the "overview effect" by *White* (1987).

Past Space-Related Experience

This change in perception is evidenced in the oft repeated astronaut wish that the warring peoples could also see this view from space, for then surely they would see the insignificance of their differences. Another example comes from Russell Schweickart who, while viewing the rotating Earth beneath him, first identified "home" with Houston. As the orbiting continued, his concept of home enlarged to include Los Angeles, Phoenix, New Orleans, North Africa, and then, finally, the entire Earth. Apollo astronauts Edgar Mitchell, through his Institute for Noetic Sciences, and Russell Schweickart, through the Association of Space Explorers, both feel a responsibility to articulate the space flight experience so that many can share it (*White,* 1987).

Some emotional experiences in space were intense enough to qualify as a "peak experience." Apollo 15 astronaut James Irwin had a religious "peak experience." Upon spying a white rock matching the description of the long-sought-after "genesis rock," he felt deeply that he had been sent by God especially to find this rock that would greatly enlighten planetary scientists. This particular recognition was only part of a larger feeling of power and understanding Irwin felt on the Moon. The experience had lasting effects, for he subsequently dedicated his life to Christian evangelism. Social scientist B. J. Bluth acknowledged that many of the astronauts were deeply affected by their flight, and for some the experience radically changed their lives (*Bluth,* 1979).

Occurrences of peak experiences are not new space-related phenomena, but have long been discussed in many ways. *Maslow* (1970) has described the religious aspects of peak experiences thus: "the whole universe is perceived as an integrated and unified whole ... the universe is all of a piece and ... one has his place in it ... this of course, is a basic meaning of religious faith for many people." On a more popular level, the experience has also been celebrated in song, such as John Denver's "Rocky Mountain High" (*Denver,* 1972). Yet, the space experience has given more credibility to overview philosophies in the minds of many. Because someone has actually observed that the Earth is a spaceship and has taken photographs of it suspended in space, it becomes more real to us. Gene Cernan, who has stood in the dusty soil of the Taurus-Littrow valley powerfully expressed it: "What I saw was too beautiful to grasp. There was too much logic, too much purpose—it was just too beautiful to have happened by accident. It doesn't matter how you choose to worship God ... He has to exist to have created what I was privileged to see" (*White,* 1987).

Prospects for the Future

White (1987) considers the experiencing of the overview effect an essential step in human evolution and speculates on significant social changes as a result of this experience becoming widespread.

Inhabitants of a lunar base will indeed have a unique view of the world and probably have strong needs to discuss, argue, and explore the feelings and ideas associated with this unique view. For those participants in a community of faith the "working through" of spiritual ideas together may result in new faiths. One of the great challenges of enclosing diverse spiritual beings inside the physical boundaries of a lunar base is evolving a faith flexible enough to be inclusive, yet more meaningful than psychology. Should this be accomplished, it would be of great benefit on Earth as well.

A "community church" provides an arena for discussions of ethics and religion among a technical population with unique knowledge. New ideas should blossom in this forum for refinement of spiritual thinking. This community then becomes the focal point for interchange of these ideas with Earth. Athens will have migrated to the Moon.

CONCLUSIONS

1. The American-tradition community church is experienced in many values that may be helpful in learning to live on the Moon. They and other religious groups should get interested in contributing to lunar base planning. Scholars should prepare to evaluate the effects of religious influence in a lunar community.

2. A lunar community will become the focal point for human discussions of religion, ethics, and philosophy.

Acknowledgments. The author very much appreciated the review comments by W. S. Bainbridge and an anonymous reviewer. The essay has also benefited from discussions with B. Halliwell, J. Whigham, J. Musgrave, and T. Laity. Dr. Bainbridge and Dr. Halliwell provided many useful suggestions and encouragement for further work. The author's interest in the role of religion in space exploration comes from present-day association with the community church in which astronauts J. Glenn, E. Aldrin, and G. Carr were active members during their spacefaring days.

REFERENCES

Bluth B. J. (1979) Consciousness alteration in space. *Space Manufacturing 3: Proc. 4th AIAA/Princeton Conf.,* pp. 525-532.

Connors M. M. et al. (1985) *Living Aloft.* NASA SP-483.

Denver J. (1972) "Rocky Mountain High." Cherry Lane Music Co.

Maslow A. H. (1970) *Religions, Values and Peak-Experiences.* Viking, New York. 123 pp.

White F. (1987) *The Overview Effect: Space Exploration and Human Evolution.* Houghton Mifflin, Boston. 318 pp.

Appendixes

AUTHOR INDEX

Adorjan A. S. 119
Alberts T. E. 603
Alexander S. S. 407
Allen D. T. 647
Allton J. H. 703
Arnold J. R. 55
Arp L. D. 267
Augustine M. 513
Ayers J. K. 83

Bahadori M. Y. 653
Bahr N. J. 95
Bell L. 243
Brazell J. W. 633
Brinker D. J. 593
Bufton J. L. 209
Bula R. J. 543, 547
Burns J. O. 315, 347
Burt D. M. 423
Bustin R. 437

Cameron E. N. 189, 459
Cantrell J. N. 199
Carr C. A. 293
Chambers T. V. 119
Colson R. O. 411
Coombs C. R. 219
Cooper E. G. 603
Cornils K. 603
Cowing K. L. 353
Crabb T. M. 475
Cullingford H. 525
Cullingford H. S. 497

D'Onofrio M. 119
Daga A. W. 281
Daga M. A. 281
Davidson W. L. 677
DeBarro M. J. 579
De Young R. J. 69
Doggett W. R. 603
Donaldson D. K. 637
Dowling R. 175
Duric N. 347

Easterwood G. W. 519
Edelman R. B. 653
Eijadi D. A. 299
Elsworth D. 407

Farmer J. T. 579
Fernini I. 347
Flood D. J. 593

Gabrynowicz J. I. 691
Gallagher S. K. 563
Garvey J. M. 25
Garvin J. B. 209
Gehrke C. W. 351
Gibson E. K. Jr 437

Hall J. B. Jr. 503
Harrison F. W. 603
Haskin L. A. 393, 411
Hawes P. B. 513
Hawke B. R. 219
Haynes R. D. 597
Heiken G. 429
Henley M. W. 61
Hijazi Y. 261
Hirasaki J. K. 119
Hood L. L. 163
Hoy T. D. 3
Hubbell D. H. 519
Humes D. H. 69
Hypes W. D. 503

Ishikawa N. 489

Jacobs M. K. 475
Jenson E. B. 133
Johnson S. W. 323, 329, 347
Johnson L. B. III 3
Jones E. M. 697
Jones J.D. 537

Kai Y. 493
Kanamori H. 489
Kaplicky J. 275
Kaszubowski M. 83
Keller M. D. 497
Keller T. S. 569
Klassi J. D. 293
Knoll K. T. 683
Knott W. M. III 537
Koelle H. H. 447
Kohler J. L. 407
Kulcinski G. L. 459, 547
Kuo K. C. 351
Kuriki K. 673

Lewis R. H. 411
Li Y. T. 609
Lin T. D. 267, 483
Lindbergh C. 267
Lindstrom D. J. 411
Linfield R. P. 321
Linsley J. 133
Llewellyn C. P. 17
Love H. 483
Lu F. 379

Maguire B. Jr. 531
Maryniak G. E. 397
Matsumoto S. 493
Matthews H. D. 133
McCurdy G. 199
McEntire J. E. 351
McKinney W. S. Jr. 603
McLaren B. K. 633
McMurray G. V. 633
Meador W. E. 69
Ming D. W. 385
Morea S. 619
Morris O. G. 119
Morrow R. C. 543
Mulqueen J. A. 101
Mumma M. J. 637

Nakamura Y. 231
Namba H. 493
Nealy J. E. 69
Nelson M. 513
Ness R. O. Jr. 559
Ness S. R. 559
Nixon D. 275
Nudd G. 119

Oberst J. 231
Ogawa Y. 673
Okada T. 489

Palaszewski B. 35
Parker D. 563
Persons M. B. 3
Petro A. J. 31, 119
Pettit D. 429
Pettit D. R. 647
Phillips P. G. 139
Ponnamperuma C. 351
Prince R. P. 537

Rawlings R. P. 119
Redd F. J. 199
Reynolds K. H. 255
Rindt J. R. 559
Roberts M. 249
Robitaille H. A. 519
Rocha C. J. 293

Sager J. C. 537
Saito T. 673
Santarius J. F. 75, 459
Sartain J. B. 519
Sauer R. L. 551
Schmitt H. H. 459, 667
Schultz J. R. 551
Scott K. W. 531
Semkow K. W. 411
Senseny J. 267
Sherwood B. 237, 637

Shevchenko V. V. 155
Simonds C. H. 139
Simonsen L. C. 579
Sliwa N. E. 603
Soloway D. I. 603
Somers R. E. 597
Spudis P. D. 163, 307
Staehle R. L. 175
Stalling D. L. 351
Stark D. 483
Stecklein J. M. 119
Stern M. O. 47
Stramler J. 659
Strauss A. M. 569
Street J. J. 519
Stump W. R. 119, 139, 677
Sulkanen M. 347
Sviatoslavsky I. N. 459
Svitek T. 175

Taylor G. J. 183, 307, 329, 347
Taylor L. A. 361, 379
Thompson W. B. 55
Tibbitts T. W. 543, 547
Trotti G. 243
Tucker W. B. 453

Vaniman D. 429
Varner C. C. 119
Volk T. 525
Vondrak R. R. 337

Weidman D. J. 17
Wendel W. R. 281
Wernick J. 275
Wetzel J. P. 323, 329
Wheeler R. M. 543
Williams K. D. 299
Williams W. M. 633
Wittenberg L. J. 459, 547, 609
Wright R. L. 3

Yodzis C. W. 119
Yoshida T. 493
Young R. M. Jr. 453

Zimprich S. J. 119
Zumwalt R. W. 351

SUBJECT INDEX

A

Abort, lunar lander, 179; option, 33, 175, 180; trajectory, 33

Active Lunar Seismic Experiment, 209

Aerobrake, 6, 13, 34, 37-39, 41, 47, 51, 62, 65-67, 103, 455; mass, 39, 62, 65; orbital-transfer vehicle, 34, 47, 62, 119; use at Mars, 455; weight sensitivity, 65

Ag, see Silver

Age, Balmer Basin, 172; Balmer light plains, 172; Copernican basalts, 216; exposure, 372, 373; old lunar rocks, 157; Reiner Gamma, 158; relationship to regolith thickness, 185, 186; test subject, 566, 571, 573; Tsiolkovsky basalts, 186

Agglutinate, hydrogen enrichment, 440; impact origin, 519; regolith content, 372; relationship to I_s/FeO, 372; titanium in glass, 190

Agriculture, Biosphere II, 513-516; hydroponic, 245; lunar, 408, 521, 551, 667, 670, 699; special-purpose mineral, 387; regolith soil medium, 407

Al, see Aluminum

Alaska, 306, 397, 696, 700, 701; settlement, 698

Albedo, floor of Grimaldi, 157, 158; lunar, 156; lunar distribution, 156; northwest of Lichtenberg, 159; northwestern Oceanus Procellarum, 159; Reiner Gamma, 158; western Oceanus Procellarum, 160

Alloy, Ca-Li, 427; Fe-Si, 411, 417, 421

ALSE, see Active Lunar Seismic Experiment

ALSEP, see Apollo Lunar Surface Experiments Package

Aluminum, abundance in anorthosites, 170; abundance in highland soils, 170; anorthite-derived, 170, 408, 424, 426, 427; concentrations around Mare Smythii, 167, 170; construction material, 136, 240; difficulty in extracting from regolith, 421; domes as shelters, 283; effects of lunar environment, 331, 332; HF acid-leaching process, 476; impact target, 142; lunar resource, 199, 227; metal, 423; olivine component, 365; phosphate sink, 521; propellant, 199, 206, 207, 433, 447, 450; pyroxene component, 365; reduction with sodium, 425; regolith as source, 361, 374; source of soil acidity, 519; spinel component, 368; support structure for regolith shielding, 581, 589; terrestrial production technique, 424; tobermorite component, 387, 389; use in collapsible structure, 263, 266; vapor deposition in zero-g, 333; zeolite component, 386

Ammonia, 97, 407, 432; conversion of fish wastes to nitrates, 515; fixing in distillation processes, 552; lunar atmospheric gas, 338; magnetoplasmadynamic propellant, 37-40, 42, 44, 45; nitrogen conversion by bacteria, 547; NASA potable water standards, 551; oxidation processes, 553; pyrolitic extraction from regolith, 395; recovery with ion-exchange processes, 554; removal by ECLS, 507; removal in water recovery from urine, 246; water distillation processes, 551, 552; working fluid in thermal control, 579, 580, 582, 585, 589

Angle of repose, 140

Anorthite, 170, 484

Anorthosite, 379, 365

Antarctica, 175, 244; analogy to space settlement, 237; atmospheric ozone, 244; comparison to the Moon and Mars, 243; exploration, 175; nuclear power, 176; Planetary Testbed, 243; plate, 244; research stations, 244, 245; wind-turbine power, 246

Antenna, Apollo LRV, 622; microwave communications, 27; microwave for heating regolith, 614; radar altimeter, 210; radio telescope, 322, 327; space station, 27

Anthropometry, 282

Apollo 11, 620; basalt, 170, 186, 189, 366, 370, 381, 469; candidate base site, 668; landing site, 159, 369; regolith, 190, 194, 610, 612; religious ceremony, 703

Apollo 12, 330, 620; basalt, 189, 368, 371; landing accuracy, 179; landing site, 168, 213, 343; lunar module interaction with Surveyor 3, 142, 331; retrieval of parts of Surveyor 3, 331; soil composition, 419, 420, 437, 610; Suprathermal Ion Detector Experiment, 184

Apollo 13, impact of S-IVB as seismic source, 343, 348

Apollo 14, 620; breccias, 362; landing site, 168; meteoritic component in rocks, 370; modularized equipment transporter, 158, 620; soil mechanics measurements, 140; soil samples, 433; Suprathermal Ion Detector Experiment, 184

Apollo 15, 214, 620, 622; basalt, 189, 365, 368; breccias, 362; gamma-ray spectrometer, 156, 190; heat flow experiment, 168; landing site, 172; laser altimeter, 209; LRV, 209, 620; lunar module ascent, 343; soil samples, 430, 433; Suprathermal Ion Detector Experiment, 184, 343; X-ray fluorescence experiment, 156

Apollo 16, gamma-ray spectrometer, 156, 190; highland samples, 362; landing site, 185; native iron in breccias, 371; soil, 430, 437, 443, 487; soil concrete component, 483; soil hydrogen retentivity, 443; soil ilmenite content, 441; sphalerite, 371; troilite, 371; X-ray fluorescence experiment, 156

Apollo 17, basalt, 189, 190, 366, 370, 429; candidate base site, 668; deep drill core, 444; double drive tube, 444; heat flow experiment, 168; high-FeO soils, 373; high-Ti basalt, 381; ilmenite, 367; landing site, 159, 194, 227, 580, 581; laser altimeter, 209; longest exposure to one-sixth g, 353; longest lunar-surface EVA, 569; LRV, 209, 632; Lunar Ejecta and Meteorites experiment, 334; lunar module impact, 185; Lunar Sounder Experiment, 203, 209; orange and black glass, 167, 195, 429, 437; region, 190, 191; regolith, 190, 372, 373, 395, 434, 443, 469; surface temperatures, 329; total traverse distance, 620

Apollo Lunar Surface Experiments Package, 333; detection of S-IVB impact, 343; durability, 331; lunar atmospheric measuring instruments, 324, 337; magnetometer, 343

Apollo program, 32, 33, 111, 125, 172, 176, 249, 337, 339, 397, 677, 684, 688; LRV, 613, 619; NASA management structure, 687, 688; reference for lunar atmospheric modification, 337, 340

Apollo site selection process, 216

Ar, see Argon

Architecture, 237-241, 255, 259, 281-285, 290; definition, 238, 281, 282; effect of lunar gravity, 282; history, 238-240, 284; lunar base, 275, 282, 283, 290; lunar subsurface, 293, 297; physiological considerations, 282; provision of essential life support, 284; role in building civilization, 238

Argon, solar wind flux (^{36}Ar), 339; detection during lunar night, 338; endogenous lunar gas, 339; effect on cement hydration, 487; lunar thermal escape constant, 339; lunar-derived, 48, 66; regolith content, 393, 487

Aristarchus, objective of robotic traverse, 402

Armalcolite, 369

Artificial atmosphere, 342, 347, 348; density, 348; formation, 348; limitation by high escape rate, 342; transport processes, 349

Ascent, 140; abort option, 133, 175; acceleration requirement, 123; Apollo 15 LM, 343; dust mitigation operations, 332; emergency, 128; expendable vehicle, 104, 109; gravity losses compared to descent, 64; lunar, 15, 121; lunar trajectory, 111, 116; magma, 167; reusable vehicle payload, 109, 111; stage, 107, 179, 180; stage, Mars, 678; vehicle, 5, 9, 25, 27, 31, 34, 104, 109; vehicle redundancy, 148; velocity requirement, 123, 449

Asteroid, target for laser altimeter, 217; near-Earth, 411

Asteroid belt, 660

Astrometry, 319, 321

Astronomical observatory, communication system, 327; effects of lunar environment, 334; location criteria, 185; micrometeorite hazard, 332; power source, 326; radio, 163, 169, 174, 323, 325-327, 337, 349; site selection, 169, 176, 186

Astronomy, 181, 183, 315; advantages of lunar site, 319, 329, 334; contamination and interference, lunar, 324, 327, 347, 349; designated areas, lunar, 186; geological factors, 183; incompatible lunar operations, 186, 327; lunar activity, 104; lunar base mission, 475, 476; neutrino observation, 317; optical, 325; quantum-limited heterodyne, 637

Astrophysics, evolution of stars, 318; neutrino observations, 318; planetary, 159, 319

Atmosphere (life support), Biosphere II, 513, 514; carbon dioxide addition by plants, 535; carbon dioxide removal, 506; CELSS, 528, 531, 537, 543; containment in lunar architecture, 281-284, 289; effects of sealed chamber on crop growth, 541; effects on compaction of concrete, 491; lunar habitat, 430, 508, 519, 522, 548, 549; nitrogen component for lunar base, 520; purification with biological systems, 516; regenerated, 537; removal of undesirable volatiles, 532; revitalization, 126; spacesuit, 660; use of lunar carbon, 470

Atmosphere (lunar), 28, 183, 186, 204, 212, 217, 251, 268, 315, 329, 337-340, 344, 348, 361, 380, 433, 536, absence, 322; absence of neutral gas, 322; Apollo data, 337, 347; artificial, 183, 184, 186, 342, 347-349, 472; charged-particle density, 349; contamination, 184-186, 210, 339, 347, 348; daytime, 329, 344; density, 338, 341, 342, 347, 349; diffusive transport mechanism, 349; dissipation, 347; effect of Apollo missions, 184; growth, 186, 341, 342, 347, 349; helium component, 339; impact-vapor component, 183; interference with astronomy due to lunar base, 347; lack of absorbing components, 329; lifetime of component gases, 343;

C-5

long-lived, 342, 347; loss through solar wind stripping, 347; lunar-derived, 407, 480, 481, 520, 547; meteoritic shield, 330, 371; modification by lunar base activities, 337, 340, 341, 344, 349, 433; natural sources, 337; neutral component, 321, 339, 349; nighttime, 329; nonexospheric mass, 342; observations of Apollo exhaust gases, 343; optical quality at lunar surface, 337, 344, 349; plasma-shielding effects, 347, 348; raman scattering, 202; response to gas releases, 344; solar wind as source, 338; solar wind component, 183; solar wind removal of gases, 341, 342, 347; solar wind shield, 339; sources, 339, 347; steady-state model, 347; steady-state near lunar base, 349; thermal escape, 339, 342; total mass input rate, 337; transient, 324, 339

Atmosphere (martian), 210, 678, 680

Atmosphere (terrestrial), 179, 240, 244, 293, 316, 317, 319, 329, 338, 342, 519, 520, 549, density, 342; impediments to interferometry, 321; loss of helium-3, 468; threat to tethers, 58

Au, see Gold

Australia, 402, 514, 516, 697-701, history, 697-701; lunar base analogy, 697, 698; settlement, 698, 699; solar-electric automobile race, 402

B

Ba, see Barium

Bacteria, radiation resistant, 241

Bamboo, building material, 296; transport as seeds, 296; use in lunar biosphere, 296, 297

Barium, interaction with solar wind, 348; feldspar component, 365

Basalt (lunar), ages, 164; Apollo 11, 170, 189; Apollo 15, 365; association with pyroclastics, 170, 171; chromite component, 368; coring, 171; electrolysis, 419; electrolysis of iron-rich simulant, 418; feldspar compositions, 365; genesis, 366; high-titanium, 170, 186, 187, 190, 222, 227, 373, 381; ilmenite, 159, 160, 366, 368; KREEP content, 168, 171, 172, 362; lava tubes, 287, 288; low-titanium, 189, 190; lunar, 156, 189, 362, 368, 380, 393, 443; magma, 171; mare sulfur content, 429; olivine, 365, 380, 381; petrogenesis, 365; plagioclase, 365; pyroxene, 362, 365; relationship to mascons, 168; spinel, 368; sulfide components, 371; titaniferous, 159, 190, 369, 469; troilite, 370; Tsiolkovsky, 187; very-low titanium, 190, 362; very-high potassium, 362; vesicular, 443; water holding capacity, 520; xenolith component, 380

Basalt (terrestrial), 362, 380; alkali, 380; Icelandic, 216

Basalt flows, 173, 185; Mare Smythii, 163, 164, 168, 170,171; Orientale Basin, 168

Base construction, 29, 31, 33, 34, 181, 213, 273, 281, 519, 673; mobile work platform, 633; mission, 35, 36; potential of calcium cements, 289; relevance of local roughness, 213; use of concrete, 273, 497, 499; use of tension-compressed columns, 270

Base design, 26, 135, 141, 180, 281-283, 505, 597, 602; architectural semiotics, 284; relationship to Biosphere II, 297; relationship to spacecraft design, 283; validation, 673

Base site, 170, 171, 173, 179, 180, 213; geological field work, 311; geological usefulness, 222; landing pad, 139, 143; lunar farside, 668; lunar limb location, 163; Mare Smythii, 164, 170-173; polar, 178; potential hazards, 214; selection, 143, 163, 171, 209-214, 216, 217, 311; survey, 178; teleoperation node, 171; traverses, 168, 311; verification, 143, 311; visibility of Earth, 140

Basin, crustal thickness, 173; ejecta, 172, 308, 469; formation, 380; geology, 172; impact, 362; mare, 380; mascon, 168, 173; radial subsurface thermal structure, 173; seismic structure, 173; subsurface velocity structure, 173

Base maintenance, 3; mission, 35

Battery, 668; Apollo LRV, 621, 628-630; rover, 70; Na/S, 246, 326, 431; power storage system, 593, 594, 596; sulfur-based, 431

Be, see Beryllium

Bed rest, antiorthostatic, 570; changes in bone-mineral content, 573; physiological simulation of weightlessness, 570; skeletal effects, 569-571, 573

Bedrock, excavation, 171; interface with regolith, 171; ore deposits, 408; source of regolith, 330

Beryllium, 639

Biology, detection on other planets, 351; gravitational, 239, 356

Biome, 514

Bioreactor, conversion efficiency, 674; use in CELSS, 675; water treatment, 675

Biosphere, 293; artificial, 293, 295-298, 393; CELSS applications, 294; lunar habitat, 296; requirement in space travel, 293; terrestrial, 241, 293, 296

Biosphere II, 297, 518; agriculture, 515, 516; animals, 515; arthropod species, 516; atmosphere, 513, 514; biomes, 514; construction, 516; crew, 516; description, 513; ecosystems, 517; equilibrium biomass, 514; fungus species, 516; hydrosphere, 513; insect species, 516; marine systems, 513; mission control center, 514; pesticides, 516; plants, 516; power sources, 513; project goals, 513; rain forest analog, 514; test module, 516-518

Boulders, 186, 326

Breccia, gas concentration, 438, 440; importance of friability, 309; lunar soil component, 487

Bremsstrahlung, 75, 78, 79

Building, code, 268, 270, 277; complex, 261; components, 245, 287, 296; illumination, 303; lunar, 290, 701; materials, 261, 296, 697; multistory, 261, 265; site, 71; structure, 261; technology, 261

Bulk composition, Moon, 173

C

Ca, see Calcium

Cadmium, abundance in lunar pyroclastic deposits, 431; photocell component, 431

Calcium, alloy with lithium, 427; anorthosite source, 167; armalcolite component, 370; cement, 289, 483, 484, 486; essential plant ion in lunar soil, 520; metal, 427; olivine component, 365; phosphate sink, 521; propellant, 206; pyroxene component, 206, 363, 365; reducing agent, 424, 425, 427; smectite saturation, 389; tobermorite component, 386; zeolite component, 388

Capital, costs, 47-50, 52-54

Carbohydrate, 528, 529; human dietary need, 525; major food type, 525; potato source, 529

Carbon, 528; abundance in regolith, 393-395, 411, 430, 609, 610; activated, 505, 552; adsorption beds, 552; by-product of helium-3 production, 471, 472; component of methane in lunar regolith, 610; compounds, 338, 550; conversion to carbon dioxide, 553; correlation of abundance with soil maturity, 437; correlation with I_s/FeO, 373; export to Moon from Earth, 504; flow through CELSS, 525; gases for use in agriculture, 408; loss through photorespiration, 297, 531; lunar and terrestrial abundances compared, 393; lunar base requirement, 473; mineral processing reagent, 423; mining, 394; organic, 351, 554; organic content of planetary samples, 351; pyrolitic extraction from regolith, 394, 470; solar wind-derived, 338, 361, 369, 372, 373, 411, 421, 609; steel, 136; total lunar abundance, 393; use in lunar manufacturing, 470; use in regenerative life-support systems, 177; waste conversion, 561; woven fibers, 275, 277, 279

Carbon dioxide, 80, 522; abundance in regolith, 610; addition to atmosphere by plants, 535; adsorption on smectite surfaces, 389; adsorption with molecular sieve, 615; assimilation by plants, 520, 537; buffer mass reservoir, 525; by-product of helium mining, 470, 472, 475, 549, 616; combustion product, 395; concentration in crop-growing area, 522; concentrator in ECLS, 504; conversion from urea, 553; cycling period in Biosphere II, 514; desorption of molecular sieve, 506; diurnal fluctuations in closed agricultural system, 534; effect of concentration in potato growth, 543-546; fixation by plants, 297, 520, 522; fluxes during crop growth, 525, 528; human production vs. plant usage, 520; laser, 642; loss due to atmosphere leakage, 549; lunar atmospheric gas, 329, 338; lunar-derived, 547; maintenance during CELSS operation, 528; martian atmosphere, 638; monitoring during CELSS operation, 528; natural laser, 638; normal atmospheric concentration, 297, 520; plant requirement, 539; plant respiration rate, 549; product of oxygen plasma reactor, 561; production from methane, 521; production in anaerobic digestion process, 521, 522; pyrolitic extraction from regolith, 184, 395, 610; regenerative removal unit, 506; relationship between availability and crop harvest, 520; relationship to lunar transient phenomena, 408; removal by ECLS, 504, 507; removal from atmosphere, 126, 177, 388, 504, 506, 521, 543; removal in CELSS, 543; requirement for lunar base agriculture, 549; requirements by different crops, 528; response of plants to atmospheric concentration, 525; role in photosynthesis, 541, 543; Sabatier reduction unit, 506; separation from hydrogen, 521; separation from methane, 521; source of oxygen, 480, 507, 508; storage for photosynthesis, 296; storage for transportation, 506, 615; supply at soil surface, 520; symbiotic fixation, 520; uptake by crops, 522, 528, 534; utilization, 542; wastes as source, 520, 521

Carbon monoxide, by-product of helium mining, 475; relationship to lunar transient phenomena, 408; removal from atmosphere by biological systems, 517

Carbonate, equilibria in soil-plant systems, 519

Carbothermal reduction, regolith processing, 476

Cash-based operation, lunar base conversion, 700

Cd, see Cadmium
CELSS, 239, 299, 517, 525, 530, 531, 537, 538, 544, 546, 551, 556, 563, 673, 674; application of solar optics, 297; biomass production, 544, 546; bioreactor, 675; bioregenerative, 519; candidate crop plants, 543; control system, 538, 543; crew size for stability, 676; crop management, 528, 546; demonstration, 556, 673, 674; ecological equilibrium, 538; electrical lamps, 543-545; environment tradeoffs, 544; food plants, 531, 534; gas exchange, 388; habitat, 675; integration into lunar habitat, 296; limiting factors, 543; mass of equipment required per person, 700; module, 300, 301, 302, 303; optimization of productivity, 543; plants, 534, 543; required pressurized volume, 294; suitability of potato plants, 543; use of lunar-derived sulfur, 433; use of solar radiation for plant growth, 544; use of zeolites, 387; waste-material separation, 356
Cement, 389, 483, 497; bond with aggregate, 487; component of concrete, 385, 389, 484, 490, 491, 497; constituents, 289, 483, 484, 486; dehydration reactions, 498; effects of inert gases on hydration, 487; hydration, 491; mass requirement for concrete processing, 273; paste, 491; plant, 494; Portland, 484, 489-491, 498; production, 267, 489; use of pyroclastic materials, 228; use in lining walls of subsurface facilities, 499; use of frozen paste in mixing concrete, 490
Centrifuge, centrifugal force gradient, 354; Coriolis forces, 354, 355; design considerations for human use, 354, 355; high-g adaptation data for dogs, 573; lunar base, 353, 355, 356; motion sickness produced by head movement, 355; regular use to decrease adaptation time, 355; sleep in rotating gondola, 355; space station, 354, 355
Ceramic, polyaluminate electrolyte, 432; radiation shielding, 408
Cesium, in tobermorites, 387; removal from water by zeolites, 388
Chemical engineering, 647
Chemical processing, 398, 405, 475, 476
Chemistry, basalt, 362, 363; fluorine, 423; industrial, 228; lunar ionosphere, 339; plagioclase, 365; pyroxene, 363, 365; remote sensing, 308; spinel, 366, 368; stellar outflow, 318; troilite, 371
Chlorine, abundance in lunar pyroclastic coating, 430; appearance in oxygen-plasma conversion, 561; mineral processing reagent, 423; paucity on Moon, 361; potential lunar sources, 669; water disinfection, 552, 553
Chromite, 379
Chromium, 365, 366, 368, 370, 379; basalt component, 216; heavy metal in lunar soil, 520; layered igneous complex, 379; use in distillation processes, 552
Church, psychological link to Earth, 703
Cislunar space, 67, 238, 239, 399
Civilization, 238, 239, 281; interstellar travel through cloning, 643; lunar, 237, 240, 241; space, 237, 239
Cl, see Chlorine
Co, see Cobalt
CO_2, see Carbon dioxide
Cobalt, 365, 412; component in native Fe metal, 371; lunar-derived, 408
Colonies, bacterial, 296
Colonization, interstellar, 637; lunar, 3, 4, 47, 54, 199, 206, 261
Colony, lunar, 303, 347, 385, 433, 551, 685, 686; manufacturing, 472
Comet, lunar atmospheric component, 183; origin of Reiner Gamma, 158
Commercialization, fusion power, 466, 468; potential of lunar base, 475, 479, 481, 482
"Common heritage of mankind" provision, absence in Outer Space Treaty, 692; cause of concern for spacefaring nations, 692; concept in international space law, 691; confusion with "province of all mankind" provision, 692; interpretation of US government, 692; limitations in Moon Treaty, 693; political aspects, 692; Moon Treaty, 691, 692; Sea Treaty, 691
Communication, 34, 95, 133; continuous link, 140; delay in Mars mission, 660, 677; engineered planetary lasers, 638, 639; hard line, 137; importance to isolated crew, 660, 675; interstellar, 637, 638, 643, 644; line-of-sight relay stations, 311; lunar base link to Earth, 163; lunar outpost to main base, 170; lunar satellites, 327; observatory antennas, 327; required for astronomical observatory, 327; teleoperation, 311; time, 393; units as impediments to astronomy, 325
Communications, Apollo LRV, 622, 628, 631
Communications satellite, 35, 44; Echo, 249
Communities, ecological, 533; extraterrestrial, 697; lunar, 697; martian, 697; microbial, 516, 531-533, 536; rhizosphere, 532; sustaining on the Moon, 239
Community, Alaskan development, 700; economic limitations, 697; lunar, 303, 703, 704; lunar analogs, 704; lunar challenges, 703; number of members for stability, 675; self-support, 697, 700
Community church, American, 703, 704; arena for discussions, 704; lunar, 703; psychological link to Earth, 703; role in alleviating social tensions, 703; role in developing social relationships, 703
Computer, control of ECLS, 296; control of lighting for plants, 539; control system for CELSS, 538; navigation system of Apollo LRV, 628; reduction of crew workload, 33; role in telerobotics, 603; sensors in Biosphere II, 517
Concrete, 240, 267, 289, 290, 389, 489; advantages as lunar construction material, 489; compaction, 490, 491; component materials, 273, 289, 489; compression, 267, 269; cracking due to air leakage, 272; curing, 490; desirable qualities, 267; effects of gravity, 489; effects of vacuum, 269, 270, 489, 490; hydration, 490, 491; hydrogen component, 273; mixing procedure, 490, 491; plant, 268; prestressed, 267-269, 273, 274; production method, 489-491; shielding, 240; structures, 267, 273, 274; nonbearing member, 491; precast, 267, 268, 273; recapture of free moisture, 273; regolith aggregate, 259, 389; reinforced, 269, 289; tank, 267; tensile stress, 269; tension member, 270; truss construction, 273; use in structural members, 491
Confinement, atmosphere, 282; conditions at lunar base, 287; consequence of life at lunar base, 703; effects on personality, 703; fusion reaction, 79; geometry in fusion rocket, 76, 78; magnetic "bottle" in fusion reactor, 76; plasma energy time, 79
Construction, 241, 259, 275, 315, 322, 232, 326, 489-491, 519, 633, 673, 679; Alaskan, 698; Antarctic, 245; Biosphere II, 516; capabilities, 266, 289; completely shielded base, 252; concrete, 267, 273; conditions in lava tubes, 289; conventional practices, 301; difficulty, 283; danger to workers, 289; effects of communications time delay, 309; efficiency, 289; equipment, 633, 679; EVA, 250, 289, 296; floating foundation, 273; gantry frame, 275; history, 294; international treaty questions, 283; lava tube options, 289; loading conditions, 267, 268; materials, 259, 289, 356, 385, 389, 489, 647, 700; manual operations, 261; martian, 678; masonry, 289; methods, 259; mobile gantry, 275; mobile work platform, 633, 634; orbital, 237, 341, 604, 662; planetary methods, 679; regolith difficulties, 273; resources, 240; shield wall, 275; solar reflectors, 613; spaceframe, 289, 290; subsurface, 296; surface, 284, 285, 296; surface stability, 337; technology, 285, 325; terrestrial analogs, 296; terrestrial masonry, 240; transportation, 275; verification of integrity, 275; workers, 289
Controlled Ecological Life Support System, see CELSS
Copernicus Crater, objective of robotic traverse, 402
Copper, discovery in Alaska, 698; magnet component, 77; rarity on Moon, 421; use in distillation processes, 552
Core, Apollo samples, 373; deep drill, 444; deep regolith sampling, 609; drilling device, 309; galactic, 316; globular cluster, 318; lunar, 173, 321; lunar base structure, 267, 270, 272, 273; protostellar, 318; source of perturbations in Earth's rotation, 321
Core sample, collection by autonomous vehicles, 604; Shorty Crater, 444
Corn, efficiency of carbon dioxide fixation, 297, 520, 522; suitability for lunar biosphere, 297
Cosmic ray, causes of defects in regolith material, 611; flux during solar flare events, 173
Cost, burden of base crew rotation, 450; commercial sample return mission, 402; comparison of Moon- and Earth-derived propellants, 448; delivery of lunar oxygen to Earth orbit, 453, 457; deployment of astronomical observatory, 186; deuterium-helium-3 fusion reactor, 466; Earth-Moon transportation, 398, 470; ECLS, 503; electricity from fusion power, 466; expendable module, 15; flight-system, 175; fusion power plants, 473; helium-3, 466; initial ECLS, 503; large-scale lunar development, 284; life-cycle, lunar transportation system, 32; life cycle, space transportation system, 448; lunar base construction, 35; lunar base, 137; lunar helium-3, 472, 473; lunar lander, 116, 124, 130, 131; lunar lander repair, 52; lunar lander return to LEO, 123; lunar mining, 550; lunar production of helium-3, 470; lunar-produced aluminum, 447; lunar-produced oxygen, 447, 457; maintenance, space shuttle, 32; mass launched per person at lunar base, 700; metabolic due to wearing spacesuit, 662; mining, 289; mobile miner, 434; operating, expendable transportation system, 15; operating, lunar lander, 52; operating, reusable transportation system, 11; operating, space shuttle, 31; operating, transportation system, 49; orbital maintenance facility, 32; orbital solar-electric power, 401; orbiting stations, 53; OTV, spare parts, 64; payload delivery from Earth to Moon, 249, 296, 450, 543-545, 549, 593, 602; pneumatic and air-supported structures, 249; production of lunar propellants, 448; replacement, expendable transportation system, 11; reusable transportation system, development, 11, 15; ring-laser gyro, 126; round trip to Moon per passenger, 450; solar electric automobile race,

402; solar-powered orbital transfer vehicle, 43; space transportation, 116, 119, 249, 319, 393, 401, 447, 448, 450, 457, 699; surface-based radar, 126; teleoperated rover, 402; telescope, 325; terrestrial electric power, 401; tether platform, development, 67; transportation, 31, 35, 49, 51-53, 64
Cr, see Chromium
Crater, chain, 220, 221; continuously shadowed, 164, 393; density, 155, 156, 161, 164; dump site, 228; ejecta, 171, 185, 219, 308; fractured floor, 167; frequency curve, Mare Smythii, 164; micrometeorite, 371; penetration of lava tube, 220-227; rays, 171, 221; rille origin, 227; simple, 213; walls, 308
Crater counts, 140
Craters, 139, 142
Cryogenic fuel, lunar production, 356
Cryogenic storage, OTV depot, 99
Cryogenics, fuel-cell reactants, 668; handling in space, 20, 23; space-storable, 23
Cs, see Cesium
Cu, see Copper

D
D, see Deuterium
Dark mantle deposits, 170-172, 227, 434
Dark mantle materials, 195
Deimos, mission, 453, 678, 679; resource potential, 393, 411
Density, 77; bone, 570, 571, 575; charged particles in lunar atmosphere, 349; chromite, 380; concrete, 489; dark matter in universe, 316; difference between crystal and melt, 380, 381; electron density at lunar surface, 339; electrons in plasma reactors, 560; electrostatically levitated dust column, 330; fluctuations in early universe, 317; gas related to ultraviolet optical depth, 349; hydrogen, 121; helium atoms in regolith, 610; laser topographic observations, 209; lunar atmosphere, 186, 338, 340, 342, 343, 347-349, 350; lunar atmospheric ions, 340, 347, 349; lunar module exhaust, 343; lunar transient atmosphere "cloud," 324; neutral atmospheric gases, 337; olivine, 381; perturbation leading to galaxy formation, 316; propellant, 120, 130; regenerative fuel cell energy, 596; regolith, 71, 158, 185, 251, 273, 393-395, 520, 612; Reiner Gamma surface material, 158; solutions in distillation columns, 616; subsurface structure of Smythii Basin, 168, 173; tether material, 55; variations in liquid-phase turbulence, 649
Deuterium, fusion fuel, 75, 78, 81, 609, 667; resonance lines, 317
Deuterium-helium-3, cooling requirement, 466; efficiency of energy conversion, 466, 477; fuel costs, 466; fuel cycle, 462, 468, 472; fusion cycle, 464, 466, 481; fusion experiment, 460-462; fusion fuel, 461-463; fusion power development, 482; fusion power plant, 462, 463, 465, 466, 472; fusion reaction, 460-462, 464; fusion reactor, 462, 463, 465, 466; impact on electric power economy, 462; neutron production, 461; plasma, 460-462, 473; radioactivity associated with fusion cycle, 462, 463, 465, 466; tokamak studies, 473
Dielectric constant, plasma, 348
Disease, acquired immunity, 533; factor in lunar base crew size, 674; human communicable, 533; organisms in Mars mission spacecraft, 660; osteoporosis, 661; plant, 516, 532; release into lunar base environment, 519; water system as source, 552
Distillation, columns in low-gravity environments, 616, 650; cryogenic enrichment of helium-3, 616; integrated membrane evaporation, 551; lunar systems, 552; processes, 551, 552; vapor compression, 246, 551; water polishing, 552; wick evaporation, 551
Docking, 22, 47, 88, 99, 179; adapter, 146; arcing hazard, 99; automated, 17, 20, 22, 23, 63, 126; hazard, 95; mechanism, 99; operations, 90; port, 34, 85-88, 93; techniques, 99
Dome, concrete form, 499; habitable structure, 493, 494, 499; lunar module shelter, 137; pressurization, 499; volcanic, 225
Drill, assemblies on mobile work platform, 633, 634; coring device on robotic field geologist, 309; deep string, 393; platform, 634; regolith cores, 311
Drive tube, Apollo 17, 195
Dunite, layered intrusive complex, 379; olivine abundance, 365
Dust, 69, 71, 283, 330, 669; agent in decreasing reflectance, 331; atmospheric, 210; circumstellar, 638; contamination, 302, 303, 330, 334, 660, 669; degradation of thermal surfaces, 622, 626, 629; detector array, 334; dynamic effects, 334; factor in lunar surface operations, 145; global martian storm, 210; hazard to Apollo LRV, 622, 624; hazard to mechanical systems, 606; interference with astronomy, 183, 185, 186, 329; interstellar, 638; levitation, 330, 334; low-velocity, 334; mobilization by rocket exhaust, 71, 142, 186, 330, 332, 334; possible presence in lunar atmosphere, 344, 347; problem for lunar surface operations, 622; protection of optical elements, 332, 334; shielding, 329, 332-334; source of diffuse X-ray background, 317; Surveyor 3, 331; ubiquitous nature, 333, 334
Dust lock, contrasted to air lock, 669

E
Earth orbit, attained from lunar launch, 3, 5, 6, 12, 15; centrifuge facility, 354; debris hazard, 660; difficulty of radio astronomical observations, 317; ease of resupply compared to Mars mission, 660; elliptical, 47, 48, 50, 52-54, 61, 65; EVA, 603; lack of sensible atmosphere, 330; maintenance facility, 11, 31, 32, 34; site for high-precision astrometry, 321; space transportation node 102, 293, 319, 394, 593, 677; variable gravity research facility, 355 31, 34
Eclipse, solar, 28
ECLS, 29, 503-507, 509, 510; carbon dioxide removal, 506; city utility, 506, 507; closure of food loop, 504; crew size, 507; crew time requirements, 507; effects of gravity, 505; effects of lunar base composition, 506; expendables, 508; habitability module, 508; integration costs, 503; likelihood of self-sufficiency, 504; logistics, 503; lunar, 504, 505, 510; material losses, 504; mission-specific, 510; nonregenerative, 503; nuclear power integration, 505; oxygen recovery, 504, 508; power requirements, 505; prohibition against venting to lunar environment, 506; regenerative, 503-505, 510; relationship to lunar base layout, 505; reliability, 508; resupply interval, 508; safety, 507; space shuttle, 503; space station, 504, 505, 507; subsystem failure, 508; support of multiple habitats, 506; use of lunar environment, 506; waste heat, 505; water recovery, 506
Ecology, global, 514; systems, 514; nonterrestrial, 241
Ejecta, 156, 160, 161, 171, 172; abrasive effects, 142; basin deposits, 172, 308; blanket, 185, 212, 213; blocks, 213; brecciated highland crust, 308; cratering on aluminum, 142; dark-halo crater, 172; deep sampling, 157; engine blast, 144, 145, 275; flux, 142; Meteor (Barringer) Crater, 213; Orientale Basin, 157; protection, 145; threat to optical surfaces, 330; trajectory, 142
Electric propulsion, 35, 42, 56; ion system, 37; mass reduction, 45; module, 39; options, 35, 37; OTV, 35-37, 44, 401; power processing unit, 39
Electrical engineering, 675
Electricity, by-product of water production, 668; conversion to photosynthetically active radiation, 544; fuel cells, 126, 246; generation, 69, 75, 76, 245, 614; storage, 246, 602; sunlight conversion, 536; water-heating requirement, 597
Electrolysis, 423, 424, 427, 428; magma production of oxygen, 519; production of gaseous fluorine, 424, 427; production of sodium, 427; reduction of fluorides, 423; sequential, 521; water, 64, 504, 549
Electromagnetic energy, laser thermal engine, 48; lunar sounder, 203; radio frequency, 203
Electromagnetic field, use in plasma reactor, 560
Electromagnetic sounding, 173, 199
Electromagnetic spectrum, low-frequency radio array, 319; robotic sensory capabilities, 308
Electron, collisions with molecules, 560; density at lunar surface, 339; density in plasma reactors, 560; reacceleration as source of low-frequency spectra, 317; replication microscopy of Surveyor 3 tubing, 332; temperature in plasma reactor, 560; transmission microscope, 372
Electrostatic charging, source of dust disturbance; 331
Emergency, 98; airlock, 256; Apollo LRV driving mode, 624; ascent, 128; equipment cooling, 581; evacuation, 100; repressurization of lunar base, 250, 507, 508; return to LM requirement during Apollo, 622; safe haven, 89, 597; warning device, 98
Emotional behavior, effects of confined habitat, 675
Energia, 180
Energy conversion, during aerobraking, 64; efficiency of GaAs photovoltaic device, 594; electric to microwave efficiency, 614; Stirling system, 247; thermoelectric system, 247
Energy requirement, pyrolitic extraction of volatiles from regolith, 613
Energy source, methane, 675; microwaves for heating regolith, 614; nuclear fusion, 609; solar, 297; solar photovoltaic devices, 614
Energy storage, 58, 72; batteries, 176; electrical, 127, 148; lunar lander, 593; orbital, 65, 66; regenerative fuel cell, 596; night operation of VLFA, 326
Engine, ablative, 124; advanced space, 39; aluminum fuel, 450; Apollo LM, 123-125; conventional rocket, 48; cryogenic, 13; efficiency, 5, 15; failure, 124, 125; ion, 48, 54, 66, 67; laser propulsion, 70, 71; laser thermal,

48; blast effects, 135, 136, 139, 141, 142, 151, 275; lander throttling ratio, 125; lunar lander, 63, 134; lunar module, combustion products, 343; lunar module, descent, 180, 331, 332; mass, 62, 71; multipurpose lander, 119; N_2O_4/MMH, 125; O_2/H_2, 63, 124; OTV, 62, 63, 125; pressure fed, 124; pump fed, 124, 125; RCS, 125; regenerative cooling, 124; relationship between thrust and chamber cooling requirements, 125; reusable, 20; RL-10, 13, 113, 181; rocket, 332; service propulsion system, 180; space shuttle, main, 125; specific impulse, 15, 63, 71; technology, 3, 13, 63; temperature, 63; thrust, 71; XLR-132, 180

Engineering, civil, 279; critical issues for lunar astronomical observatories, 323; electrical, 675; environmental control, 238; geological, 238; human factors, 97, 237; lunar research, 701; planning for protection of astronomical optics, 329; structural, 238, 275; system, 683, 684, 686, 687; system safety, 98; tether, 58

Environment, Antarctic, 243, 245; artificial gravity, 356, 679; astronomical, 329, 334, 349; contamination, 184, 519; controlled, 228, 301, 541, 543; damage, 186; effects on structural design, 251; erosion, 331; gravitational, 616; hard radiation deflection, 173; human impact, 199; lava tube, 288, 289; low Earth orbit, 301, 329, 332; lunar, 148, 212, 237, 241, 251, 266, 267, 283, 294, 308, 323, 329, 332, 334, 337, 339, 341, 343, 344, 347, 348, 380, 385, 489-491, 506, 553, 579-581, 589, 603, 606, 607, 611, 613, 620, 633, 667, 669, 674, 677-679, 703; lunar base, 579, 581, 604; magnetically shielded, 661; martian, 574, 677; martian thermal, 660; microbial paradise, 506; micrometeoroid, 327, 332; nonhabitat facilities, 506; optimal gravity, 569; optimal strain, 571; oxidizing, 653; plasma, 337, 339; potato growing, 543; reducing, 369, 370, 372; rotating centrifuge, 354; seismic, 231-233; seismic, terrestrial, 232; shirtsleeve, 34, 250, 619; solar, 90; source of microorganisms, 533; south pole, 581, 584; space, 55, 97, 125, 237, 241, 253, 284, 301, 303, 329-333, 547, 569, 570, 660, 694; space station, 504, 579, 582; surface, 288, 293, 329, 330, 334; Surveyor 3 exposure, 331; terrestrial, 519, 522; thermal, 135, 327, 582, 589; vacuum, 99, 136, 253

Environmental control, 116, 126; lava tube, 219; lunar base, 503; space station, 296, 554

Environmental Control and Life Support, see ECLS

Environmental control engineering, 238

Environmental control system, 503, 559, 597

Escape velocity, compared to exospheric thermal velocity, 342; compared to thermalized hydrogen and helium, 339; lunar, 361; Phobos, 662; relation to atmospheric mass loss rate, 342; relation to thermal evaporation, 347

Europium, anomaly, 366; plagioclase component, 365

EVA, see Extravehicular activity

Evaporation, cause of porosity in concrete, 490; dispersal of transient atmosphere on Moon, 324; Jeans' escape, 337, 342; membrane, 246; prevention in concrete with airtight covering, 490; production of thin-film solar cells, 431; regolith heating, 615; thermal loss of atmosphere, 347; thermoelectric integrated membrane, 551; vapor-compression distillation, 551; water from concrete, 498, 499; water reclamation system, 505; wick, 551, 552

Exobiology, lunar laboratory, 351

Exploration, Arctic and Antarctic, 175; autonomous, 604; deep-space, 653; geological, 164, 171, 172; geophysical, 172, 174; geoscience, 170; goals for robotic geologists, 307; human, 88, 207, 385; long-term space, 574; lunar, 3, 25, 35, 64, 101-104, 159, 170, 175, 199, 207, 307, 308, 311, 312, 353, 356, 619, 633, 667, 681; lunar orbital, 207; martian, 353, 677-679, 681; planetary, 243, 293, 385, 673, 681, 688; regolith, 189, 195; robotic, 25, 96, 103, 109, 171, 199, 311, 688; solar system, 207; space, 75, 691, 692, 703; traverse, 171

Explosion, 318

Export earnings, early Alaskan analogy with lunar base, 700; early Australian analogy with lunar base, 697, 700

Exposure age, lunar soil, 372, 373

Extinction, flame tip in microgravity, 655; infrared due to interstellar dust, 638; microbial species in isolated human groups, 533

Extraterrestrial material, asteroidal source, 393

Extravehicular activity, 84, 85, 88, 143; Apollo, 353, 622, 625; construction, 250, 289, 296; contaminated spacesuit, 99; control center, 84, 88; cost, 250; crew, 27, 28; Earth-orbital, 603; electrical arcing, 99; hazard, 95, 99, 134; longest lunar, 353; lander servicing, 151; lunar surface, 146, 178, 275, 277; micrometeoroid protection, 84; operations, 143; orbital depot, 92, 93; propellant loading, 89; retriever robot, 99; spacesuit, 90, 660; traditional caution, 289; thermal protection, 84; transfer from lander to base, 136, 143; vehicle maintenance, 90

F

F, see Fluorine

F, stellar spectral type, 637

Farming, early Australian, 699; fish, 245; lunar soil, 519; part of integrated system, 521; shrimp, 245

Fault, detection, 125, 510, 606; thrust, 232

Fault system, 222

Fe, see Iron

Feldspar, component of anorthosite, 362; component of highland soil, 184; glass composition, 184; plagioclase, 365; potassium, 365

Fertilizer, anaerobic digester effluent, 521; conversion of solid human waste, 675; product of bioreactor, 674, 675; use of algae and bacteria, 296; use of lunar sulfur, 228; use of smectites, 389

Fiberglass, components of Apollo LRV, 629; decking, 263, 266; lunar-derived, 519, 520

Fiber optic network 26, 27

Field geology, basic tasks, 309; goal, 171; lunar, 307; robotic, 308, 309, 311

Field study, communications time delay, 309; dark-mantle deposits, 171; geologic, 174, 307-309, 311, 312; Purkyne U Crater, 171; robotic, 307, 309, 312; simultaneous human and robotic, 311

Field work, human participation, 308, 309; lunar, 309; planning, 171; telepresence robot, 309; terrestrial, 307, 309

Finer fraction, importance, 373

Fines, energy requirement for volatile extraction, 613; pyrolitic volatile extraction, 612, 613; solar wind content, 361, 395, 430

Fire, Antarctic nuclear plant, 176; detection and supression system, 126; electrical arcing, 99; hazard, 99, 100, 301; safety, 653, 657

Fire-fountain, eruptions, 167, 429

Flame, 654, 655; behavior at reduced gravity, 653, 655; characteristics, 656; chemistry, 657; dependence on oxygen diffusion in microgravity, 655; diffusion, 653; effects of bouyancy, 653, 654; effects of pressure and oxygen, 655; factors in extinction, 655; factors in spreading, 655; gas-jet diffusion, 653, 654, 656; height, 656; laminar behavior, 654; low momentum, 657; morphology in microgravity, 655; propane in microgravity, 655; radiance, 655; radiation in microgravity compared to normal gravity, 655; sheet, 653; structure, 657; suffocation, 655; turbulent behavior, 654

Fluidized bed reactor, 614-616; hydrogen extraction from regolith, 614

Fluorine, abundance in lunar pyroclastic coating, 430; bonds with metals, 424; containment by nickel, 424; exchange reaction with oxygen, 424, 425; extraction from fluorite, 424, 425, 427; mineral processing reagent, 423; paucity on Moon, 361; potential lunar sources, 669; properties, 423; reagent element, 398; recycling, 426; storage, 427; transportation as NaF, 427; types of reactions with oxygen, 424; use in oxygen production, 423; use in processing uranium, 423

Food, agricultural source in Biosphere II, 515; CELSS crop plants, 531, 533; crop biomass for fish, 521; crop combinations, 537; crop growth rate, 537; crops for lunar base, 525; cultivated chlorella, 297; daily requirement per crew member, 296, 520, 534; higher plants in CELSS, 543; hydroponic systems, 519; intake compared to stool weight, 564; loop in ECLS, 504, 505; lunar base requirement, 433; lunar crop enhancement, 356; lunar export to space station, 670; minimum requirements for lunar base, 520; plants as source in bioregnerative system, 519; potatoes, 543; preparation, 597; processing, 547, 548, 549; production and carbon dioxide loss, 549; production and nitrogen loss, 548; production and oxygen loss, 549; production at Bios-3, 517; production at lunar base, 519-522, 531, 532, 536, 537, 547, 551, 556, 670, 700, 701; production from lunar soil, 520; production in early Australian colony, 698, 699; production using algae and bacteria, 296; rabbit, 534; rabbit meat, 534; recycling, 549, 559; required production area, 520; required volume for hydroponic production, 296; space required for plants, 534; supply from Earth, 505, 507, 670; webs in Biosphere II, 515

Fuel, 9, 71; deuterium-helium-3, 75, 76, 78, 80, 81; deuterium-tritium cycle, 79; economy, 48; fissile, 81; fusion, 75; fusion cycle, 75, 76, 81; mass required by fusion rocket, 78-79; proton-proton, 80; radioactive, 609; reduction by high specific impulse, 15; reduction by use of aerobrake, 13; reduction by use of tethers, 54; scavenging, 147; solid, 207; tritium, 80

Fuel cell, 148, 246, 602, 668; high energy output, 127; hydrogen/oxygen regenerative, 593; lunar base power cart, 148, 149; lunar base power system, 669, 670; nighttime power for lunar base, 148; operating temperature range, 127; OTV power system, 39; power storage, 403; product water, 127, 432; reactants, 127, 404, 432, 595, 668; regenerative, 246, 595, 596; space shuttle, 127; use with solar arrays, 596; ECLSS

power source, 126; lander power, 127; lunar rover, 70; operation, 246; primary, 595, 596; reverse osmosis, 245
Fuel production, lunar, 448
Fuel storage, space, 20, 25
Funding, 0
Fusion, conductivity changes in FeO, 414, 459

G

Ga, see Gallium
G, stellar spectral type, 637
Gabbro, anorthositic, 368; layered intrusive complex, 379; lunar, 362; olivine content, 365
Galaxy, colonization, 637, 644; spread of human life, 637
Gallium, component of lunar pyroclastic coating, 431; use in photovoltaic cells, 246, 594
Gas, abundances in lunar regolith, 395, 610; anaerobic digestion production, 521; atmospheric components, 508; biomass generation system, 245, 246; bubbles in mass-transfer system, 648; carrier of liquid for mass transfer, 647, 650; chromatography, 437, 517, 554; collection during in situ mining, 611; content of beneficiated regolith, 610, 611; control and monitoring systems, 541; controller, 509; cryogenic separation, 521; convection, 648; effect on thermal conductivity of regolith, 395; effects on lunar concrete mixtures, 487; effluent stream, 553; exchange by simple plants, 296, 297; exchange in CELSS, 388; extraction from regolith, 394, 395, 478, 614; flow rate in mass-transfer system, 648-650; fluidized-bed reactor, 614, 615; heat-transfer agent, 395; high-pressure storage system, 596; loss from concrete, 499; loss from lunar base, 509; lunar abundance, 434; lunar base pressurization, 508, 509, 547; management for regenerative fuel cells, 595; mixtures in CELSS, 388; natural, 459, 468, 470, 513; noble, 440; partial exchange in lunar base, 519; phase separation in ECLS, 505; processing facility, 615, 616; relationship to plasma, 559; removal by zeolites, 388; removal from regolith at low pressure, 395; removal of methanogens, 532; separation by zeolites, 388; separation from liquid, 553, 648; separation in CELSS, 388; silicon tetrafluoride, 423, 426; solar wind, 477, 478, 480; storage, 482, 596, 615; stream from oxygen plasma conversion, 561; sulfur, 429; sulfur dioxide, 431, 433; sulfur species evolved from pyrolized regolith, 610; trace contaminants in Biosphere II, 514; turbulent convection, 648; velocity in spray tower, 650; working fluid for turbine, 395
Geikeilite, 366
Genesis Rock, 704
GEO, see Geosynchronous orbit
Geochemistry, lunar, 366
Geodesy, radar altimeter, 176
Geophysical station, 172, 173
Geoscience, exploration, 170; lunar, 163, 164, 174, 183, 185, 186, 211, 217; lunar orbiter, 176, 209, 210; Lunar Observer, 199
Geosynchronous orbit, 27, 62, 170, 394, 401; cost of material delivery from Earth, 447; radiation shielding requirement, 239; solar-power satellite, 447, 448, 450; space transportation node, 401; transportation cost from Earth, 450; transportation cost from lunar surface, 450
Girbotol, carbon dioxide removal process, 521
Glass, agglutinate, 190, 361, 372, 385, 519; alteration to special-purpose minerals, 387, 389; atmospheric contamination during production, 184; basaltic, 387; black, 195; brick fabrication, 72; building material, 240; component of breccia matrices, 362; composite material, 398; droplet, 195; erosion by ejecta, 142, 144, 145; fiber optics, 301; formation by meteoroid impact, 519; fusion of lunar regolith, 71; lunar construction material, 389; lunar jewelry, 402; lunar processing, 402; lunar transparent, 421; optical quality, 142; orange, 195, 429; production from regolith, 184, 398, 432; pyroclastic, 429; regolith component, 385, 387, 483, 487; source material for special-purpose minerals, 387; tunnel lining, 294, 295; volatile coatings, 429
Gold, content of "pristine" rocks, 362; discovery in Alaska, 698; meteoritic element in regolith, 371; mirror coating, 639, 642
Grain, role in early Australian economy, 698, 699
Grain size, beneficiation of regolith, 476, 477, 610, 613; correlation with helium content, 610; distribution in lunar regolith, 330, 372, 609; landing surface, 140; effect on mechanical properties of soil, 487; evolution of regolith, 171; median on Surveyor 3 filter, 331; related to gas content of regolith, 437, 438, 441, 444; relationship to solar wind implantation, 190
Gravity, 659; 1/6, influence on structural design, 282; 1/6, testing of prefabricated modules, 266; anomaly, 158, 168; architectural factor, 239, 268; artificial, 92, 175, 282, 574, 661, 677-679; cardiovascular effects, 661; dependance of water processing systems, 551, 553; dependence of water quality instruments, 554; driver of buoyancy, 649; effects of wastewater use in plant system, lunar, 554; effects in diffusion processes, 647; effects on base design, 282, 505; effects on bone loss, 569, 571, 661; effects on crystal settling rates, 379, 380; effects on ECLS design, 505; effects on electrolysis, 412; effects on flame structure, 657; effects on human gait, 241; effects on human skeleton, 569, 572-574; effects on liquid-gas mixing, 649; effects on liquid-phase turbulence, 649; effects on ore processing, 409; effects on pneumatic structures, 251; effects on skeletal muscles, 661; effects on soil drainage, 533; effects on turbulence, 649; effects on bone-mineral content, 572; high, 650, 654; human adaptation, lunar, 569, 571, 574; lunar, 282, 261, 353, 355, 411, 499, 553, 569, 574, 608, 614, 622, 627, 633, 639, 648, 661, 667, 668, 670; martian, 573, 574, 647, 648; nonzero, 654; optimal environment, 569; orbital measurements, 173; Phobos, 662; physiological effects, 282, 570; reduced, 282, 573, 574, 606, 647-650, 653-657, 659, 661, 662, 668; search for lava tubes, 228; survey, 168, 173, 228; terrestrial, 69, 353, 622, 653, 654-657, 659, 662, 670; variable on space station, 661; zero, 83, 84, 96, 99, 102, 284, 353, 505, 537, 569, 570, 574, 679; zero, distribution of body fluids, 566
Gravity field, lunar, 204, 219
Gravity gradient, 90; effects on heat pipes, 601; forces, 87, 90; lunar, 205; problems, 574; stabilization, 37, 201; torque, 642
Gravity-assisted trajectories, 458
Greenhouse, Biosphere II, 516; effect, 459; lunar base, 670; module, 522
Gruithuisen Crater, objective of robotic traverse, 402
Guidance, 20; adaptive, 32-34; automated systems, 146; lander, 126, 136, 140, 146; lander radar, 144; space station, 25, 28; tether system, 57, 58

H

H, see Hydrogen
H_2, see Hydrogen
Habitat, 18, 72; atmospheric requirements, 508; biosphere, 293, 296; capacity, 669; components, 249; configurations, 255; continuously manned, 506; design, 176, 177, 250, 251, 282, 296, 297, 669; dimensions, 184; ECLS support, 506, 507; energy storage, 72; inflatable, 249-253; lava tube, 219, 225, 228, 287, 289; life-support system, 72; lighting, 297, 302; lunar, 293, 579, 593; module, 3, 18, 23, 26, 27, 134, 136, 179, 250, 255, 283, 289, 302, 400, 493, 507, 580, 597, 604, 668, 669, 678; prefabricated, 261; pressurization, 508; radiation shielding, 251, 252; regions of Biosphere II, 514; required facilities, 580; subsurface, 293, 408; thermal protection, 589, 590; volume requirement, 287, 675; venting, 183-185, 349; waste material processing, 506
Habitation, area requirement, 296; artificial gravity, 677, 679; growth, 151; lunar base, 143, 145, 151, 181, 249, 253, 281, 283, 285, 290, 293, 499, 513, 519, 633; Mars lander module, 679; planetary module, 679; polar site, 175, 302; space, 249; suitability of Mars, 393
Halo orbit, 102
Hazard, acceptable, 98; analysis, 95, 97, 98, 100; biological, 99, 100; block field, 185; catastrophic, 99; combustible, 99; control, 97, 98, 100; cryogenic, 99, 100; electrical, 99; explanation, 100; EVA, 95, 134; fire, 655, 657; hydrogen, 98, 99; identification, 95, 98, 100; impact, 99, 100, 231, 660; landing, 145; long-term, 99; lunar dust, 622; martian thermal, 660; mercury in fluorescent lamps, 301; mission, 99; operational, 100; OTV depot, 99; pollution, 99; pump cavitation, 99; radiation, 251, 475; safety, 95, 97-99; seismic, 231
He, see Helium
Heat capacity, lunar regolith, 395, 477, 478, 613
Heat flow, Apollo 17 experiment, 168; global mean, lunar, 168; lateral variation, 173; mare/highland border, 168; measurement, 168, 172, 173; probe, 172, 173; relationship to megaregolith thickness, 168, 173
Heavy lift launch vehicle, 5-9, 12, 13, 15, 17, 179, 180, 188, 593, 667
Helium, abundance in Mare Tranquillitatis, 194; abundance in regolith, 184, 187, 189, 190, 194, 393, 430, 434, 469, 477, 547, 610; abundance related to regolith exposure time, 190; abundance with depth in regolith, 195; adsorption on degassed regolith, 615; concentration in fluidized-bed reactor, 614; concentration in gas evolved from regolith, 615; content of dark mantle, 195; correlation of abundance with titanium oxide abundance, 469; correlation with ilmenite content of regolith, 441, 611; correlation with regolith size-fraction, 189, 194, 195, 610, 611; correlation with titanium content, 187, 189, 190, 193, 469, 609; cosmic, 317; depth profile in regolith grains, 610; diffusion in regolith, 615; distribution in Apollo 11 regolith, 194; extraction from regolith, 469, 470, 473, 477, 549, 610, 612, 615; fraction of gases trapped in regolith, 184; ionization detector, 437; isotopic separation, 616; lique-

faction, 615; liquid reservoir, 616; loss in sieving process, 610; lunar atmospheric gas, 338, 339; lunar resource, 361; lunar thermal escape time, 339; mining, 184, 189, 194, 341, 347, 394, 395, 609; partial substitute for nitrogen in habitat atmosphere, 548, 550; possible effect on lunar cement, 487; recovery rate from regolith, 189, 194; separation after extraction from regolith, 470; separation of isotopes, 615, 616; solar wind component, 183, 190, 194, 337, 339, 361, 374, 469, 477; solar wind implantation rate, 173; strategic storage caverns, 468; transport from Moon, 615, 616

Helium 3, 75, 76, 78-81, 184, 194; abundance in gas-giant planets, 80, 81; abundance in regolith relative to helium-4, 189, 477, 610, 616; by-products of production, 472, 475, 547-549, 609, 616; acquisition, 475, 477-482; acquisition by-products, 481, 482; commercial value, 479; cost, 466, 470, 472, 473, 477, 549; decay product of tritium, 460, 468; depletion near lunar base, 478; energy equivalent, 460, 469, 470, 472, 477, 609; enrichment process, 616; extraction facility, 482; fraction of total helium abundance, 477; fuel cycle, 482; fusion fuel, 75, 187, 195, 361, 373, 374, 394, 459, 460, 475, 477, 481, 482, 547, 549, 550, 609, 667; fusion reactor, 609, 610; fusion rocket, 76, 79; ilmenite source, 170; ion, 460, 469; low terrestrial abundance, 460; lunar abundance, 75, 460, 469, 477, 482, 609; lunar export, 170, 481; lunar-derived, 189, 469, 475, 477, 547; lunar resource, 184; mining, 80, 170, 174, 183-187, 471, 475, 477-482, 547, 612, 613, 616; nonterrestrial sources, 468; potential lunar reserves, 477; predicted demand, 472; production, 184, 478-480; properties at 2.2 K, 616; propulsion system, 75, 76, 80, 81; quantity required for terrestrial energy needs, 460; reactor radioactivity, 466; recoverable quantities, 194; regolith beneficiation, 477; regolith processing, 611, 613; solar wind as source, 460, 469, 609; terrestrial abundance, 79, 460, 468, 469, 475, 477, 482, 609; terrestrial production rate, 468, 469; terrestrial resource, 609; terrestrial sources, 468, 469; terrestrial value, 482; total energy potential, 75

Henry's Law, 412

Hg, see Mercury

Highlands, 167, 172, 185; active seismic sounding, 173; aluminum abundance, 170; Apollo missions, 362; component in breccias, 362; compositions, 362; crater density distributions, 155; crustal rock, 187; crustal thickness determination, 173; description, 185; effects of impact bombardment, 167; europium anomaly, 366; feldspar abundance, 184; feldspar compositions, 365; Grimaldi area, 157; helium abundance, 189, 469; hydrogen abundance, 443; igneous rocks, 363; ilmenite abundance, 441; iron abundance, 156; lateral variations, 171; magnesium abundance, 365; megaregolith, 168; meteoritic material, 371; mineralogy, 362; metal component, 371; Oceanus Procellarum region, 157, 160; olivine abundance, 365; plains materials, 172; plutonic rocks, 362; polymict breccias, 362; pyroxene, 365; regolith, 170, 187, 189, 273; relationship to magma-ocean theory, 366, 379; roughness, 185; source of anorthite, 408; sulfur abundance, 429; topography, 176, 185; troctolites, 368; young thrust-fault scarps, 232

HLLV, see Heavy lift launch vehicle

HLV, see Heavy lift launch vehicle

Horticulture, Biosphere II, 516

Hubble parameter, constraint provided by lunar observatories, 319; definition, 315; measurement, 316

Hubble Space Telescope, 315, 319

Human behavior, effects of life in confined space, 673; influence on lunar base design, 237, 282

Human expansion, 75, 237, 637

Human exploration, 88, 385

Human factors, 237, 659; engineering, 97, 237; hazard, 98-100

Humidity, control by artificial intelligence, 522; control in lander cabin, 126; control system, 581, 582; effect on photosynthesis, 296; exchanger, 581, 582; factor in plant productivity, 544; reclamation of condensate, 504, 506, 554; regimes in Biosphere II, 514; water reclamation from condensate, 554

Hydrogen, 64, 470, 528, 560; abundance in core samples, 443, 444; abundance in regolith, 184, 393-395, 407, 430, 433, 434, 437, 438, 443, 444, 487, 520, 610, 615; abundance related to soil grain size, 437, 438; abundance related to soil maturity, 437, 438, 443, 444; adsorption on degassed regolith, 615; alpha spectral line, 316; arcjet propellant, 37, 39, 40-42; autotrophic bacteria, 547; battery component, 28, 29, 180; boil-off rate, 39, 40; by-product of helium-3 mining, 394, 471, 472, 475, 481, 616; component of lunar atmosphere, 183; component of water evolved from regolith, 610; concentration in breccia, 438, 440; cosmic, 317; diffusion in regolith, 615; distribution related to soil-particle type, 440; distribution with depth in regolith, 444; Earth-derived, 55, 63, 447, 476, 493; enrichment in agglutinate fraction, 440; extraction from regolith, 394, 395, 408, 411, 437, 438, 470, 610, 614, 615; flow through CELSS, 525; fuel cell reactant, 127, 246, 404, 432, 593, 595, 668; ilmenite reduction, 64, 407, 423, 475, 476, 521, 522, 549, 562; ionization in biological system, 433; laminar diffusion flames, 655; lunar abundance, 393-395, 437; lunar atmospheric component, 329; lunar-derived, 146, 393, 394, 447, 450, 457, 470, 481, 547; lunar production, 394; lunar resource, 361, 437; lunar thermal escape time, 339; mineral processing reagent, 423; mining, 393, 394, 437, 444; orbital storage, 95, 99; orbital transfer, 63, 102; paucity in lunar interior, 393; plasma, 48; production from methane, 519, 521; production requirements, 394; propellant, 6, 13, 17, 28, 35-42, 44, 45, 47, 48, 56, 57, 62-64, 66, 67, 70, 71, 85, 119, 121, 123-125, 133, 134, 136, 137, 147, 148, 180, 181, 206, 361, 374, 394, 400, 407, 432, 447, 454, 479, 481, 677; properties, 423; reagent element, 398; removal by ECLS, 507; removal from organic compounds, 432; requirement at lunar base, 408, 437, 473; requirement in concrete processing, 273; requirement in water production, 521; retention by ilmenite, 441; separation from other gases, 521, 615, 616; shuttle external tank, 398, 400; silane component, 432; smectite saturation, 389; solar wind implantation rate, 173; solar wind component, 168, 337, 339, 361, 367, 369, 372, 374, 387, 408, 411, 421, 437, 438, 441, 444, 609; storage, 119, 124, 137, 615; sulfur life cycle, 433; synthesis from steam-hydrocarbon reforming process, 521; terrestrial, 49, 55, 62, 700; thermalized, 339; timescale of diffusion from regolith grains, 615; transport from Earth to Moon, 504, 678, 679; use in regenerative life-support systems, 177; wastes as source, 521, 522; water equivalent in regolith, 393; water production, 444, 601; water-derived, 432, 562; working gas in fluidized bed reactor, 614; yield after sieving soil, 438

Hydroponics, comparison to zeoponics, 388; candidate cultivation method in Biosphere II, 516; high production, 530; mechanical and control requirements, 533

I

I, see Iodine

Ice, Antarctic, 175, 244, 247; heating in concrete with microwaves, 491; possible existence at lunar poles, 393, 401, 407, 601; relative ease of dispersion in concrete mixture, 490, 491

Iceland, 215-217

Igneous activity, early Moon, 380

Igneous rock, 370

Ilmenite, 159, 170, 366-368, 408, 668; abundances at Apollo sites, 668; association with rutile, 370; association with troilite, 370; beneficiation in regolith, 408, 611; black glass, 195; compositions, 366, 368; correlation with FeO in Apollo 17 soils, 373; distribution in regolith, 611, 670; efficiency of oxygen extraction with hydrogen, 423; exposure to solar wind, 190; exsolution product of ulvospinel, 369; factor in site selection, 408, 669; grain size, 190; helium content, 170, 190, 373, 441, 668; hydrogen content, 441; hydrogenation, 367; lunar abundance, 368; lunar basalt component, 170, 362, 366, 380; regolith component, 373, 385, 408, 432, 611; lunar resource, 159, 170, 379, 380, 382, 407, 408; magnesium content, 366, 370; mining, 521; paucity in highland soil, 443; potential steel feedstock, 268; product of ulvospinel reduction, 369; propellant source, 206, 408; pyroclastic component, 228; reduction, 64, 65, 366, 407-409, 432, 475, 520-522, 549, 562; reduction with methane, 521; remote sensing, 159, 669; settling velocity in magma, 380, 381; solar-cell component, 431; source of oxygen, 155, 170, 184, 368, 379, 424, 429, 432, 519, 668; source of sulfur, 432; source of titanium, 190; stability curve, 366; terrestrial, 159, 366, 367; zirconium content, 370

Imbrian Period, 157

Imbrium region, 189

Impact, asteroidal, 164; autoreduction of regolith, 372; block generation, 213; breccias, 372; brecciation, 167; cometary, 183; damage, 90, 99, 151, 277; debris, 185; excavation, 168; fluidization, 185; gas jet on lunar soil, 158; generation of agglutinates, 440; generation of defects in regolith material, 611; generation of plasma, 168; generation of regolith, 170, 609; hard lander, 178; hazard, 99, 100, 219, 283, 660; highland bombardment, 160, 167; hydrated meteoroid, 183; iron meteorite, 213; melt, 362, 372, 374; metamorphism of lunar soil, 371; meteoroid, 220; micrometeorite damage, 408; micrometeorite damage to regolith grains, 487; micrometeoroid, 84, 220; orbital debris, 97, 99; pneumatic, 99; protection, 85, 88-90, 92, 93; remobilization of sulfur in troilite, 371; reworking of regolith, 170, 171, 372; secondary, 223; shock damage to rock, 362; vaporization of meteoroids, 183

Impact basin, 164, 172, 362

Impact crater, 140, 164-167, 213, 214, 216, 220-222
Impact deposit, 213
Impact ejecta, 161
Industrialization, lunar, 673
Industry, Alaskan salmon, 698; aluminum extraction, 424; Australian pastoral, 699; fusion power, 466, 477; lunar, 181, 432; synthesis of zeolites, 387
Infrastructure, Earth-Moon transportation, 61-65, 67; lunar, 103, 450, 476; lunar base, 103, 253, 266, 267-270, 273, 274, 450, 476, 480, 510; lunar oxygen production, 399; solar-power satellite construction, 397; space, 18, 80, 397, 399, 475, 481; space transportation, 83, 84, 93, 103, 104, 133, 385, 405
Insolation, variation at Mars, 639
Interferometer, Moon-Earth radio, 185
Interferometry, differential, 641
Internal friction, lunar soil, 140
International space law, 691, 692; Outer Space Treaty, 691, 693
International lunar base, 676
Iodine, disinfectant, 553; halogenated organics, 553; lasing medium, 69; recovery methods, 553; resistant bacteria, 553; taste, 553; water disinfection, 553
Ions, acceleration, 48, 437; altitude distribution, 340; ammonium selectivity by zeolites, 388; atmospheric, 337, 344; atmospheric energy distribution, 339, 340; atmospheric fluxes, 339, 347; atmospheric loss to solar wind, 339; atmospheric production rate, 340; atmospheric source, 342; components of silicate melts, 415; barium extraction by polarization electric field, 348; bombardment of lunar surface, 168; chromatography for testing water, 554; cyclotron, 77; detectors in SIDE, 338; deuterium, 460; discharging in electrolysis, 415; deflection by lunar magnetic fields, 173; engine, 48, 54, 61, 65-67; essential species for plants, 520; exchange in water purification, 246, 552, 553, 554; flouride compared to oxide in size, 423; flux after impact of Apollo 13 S-IVB, 343, 348; formation on lunar dayside, 339; generation from photoionization of neutral atmosphere, 339; helium-3, 460, 469; hydration as source of soil acidity, 519; magnetosheath, 343; mass spectrometer in SIDE, 338, 344; migration in electrolysis of silicate melt, 415; modern sensors, 344; orthophosphate, 521; oxide concentration in silicate melt, 412; oxygen, 416; plasma cloud, 348; production in plasma reactor, 560; propulsion, 35-39, 41-44, 56, 76, 642; reflection by magnetic mirror, 78; relationship to conductivity of silicate melt, 415; residence time in atmosphere, 340; role in electrolysis, 414; slowing in hot plasma, 462; solar wind, 339, 343, 393; suprathermal, 184; temperature in tokamak, 461; terrestrial magnetospheric, 338; toxicity of fluoride, 423; variation of atmospheric number density with altitude, 340
Ion exchange, behavior, 385
Ionization, detector, 437; plasma reactor, 560
Ionizing radiation hazard, 275, 282, 433, 659
Ionosphere, 337, 339, 340; alteration by human activities, 344; coupling to solar wind, 339; Debye shielding length, 348; density, 349; dynamics, 344; interference with terrestrial VLFA, 317; particle collision frequency, 339; plasma frequency, 349; radio wave reflection, 349; source, 337; terrestrial, 339
Iridium, content of "pristine" rocks, 362; meteoritic element in regolith, 371
Iron, abundance in lunar regolith, 156, 361, 374, 476, 520, 549; alloy with silicon, 412, 417, 421; armalcolite component, 370; association with troilite, 370; basalt component, 362; component of highland material, 156; component of plagioclase, 365; ease of reduction, 425; electrolytic production, 412; enrichment in basalt melts, 365; essential plant ion in lunar soil, 520; gamma-ray spectral lines, 190; high silicon, 421; liquid segregation from FeS, 429; lunar coins, 402; lunar processing, 402; lunar resource, 227, 405; lunar-derived, 408; metallic, 361, 362, 370-372, 374, 416; meteorite, 213; olivine component, 206; oxide in terrestrial ilmenite, 159; phosphate sink, 521; pleonaste component, 368; pyroclastic source, 228; pyroxene component, 206, 363, 365, 408; pyroxferroite component, 365; recovery by electrolytic smelting, 411, 415-417; reduction product, 64, 366, 367, 369, 371, 562; schreibersite component, 370; separation in magma ocean, 366; silicate electronic conductivity, 414, 415; solar flare heavy nucleus, 331; solubility of metal in silicate melt, 413; source of soil acidity, 519; storage container for fluorine, 423; terrestrial processing techniques, 405; tobermorite component, 387, 389
Irradiation, laser, 72; sources for photosynthesis, 543, 544, 546; temperature related to material damage, 464; ultraviolet disinfection of water, 553, 554
I_s/FeO, correlation with other indices of surface exposure, 373; correlation with solar wind abundance, 373, 374, 443; correlation with trapped ^{36}Ar, 373; relationship to agglutinate content, 372, 374; relationship to Fe-metal content, 372; soil maturity index, 372, 373, 437, 443, 444
Isolation, consequence of life at lunar base, 703; effects on personality, 703; fissionable uranium isotopes by centrifugation, 356; microbiological, 531, 533; requirement of lunar telescopes, 326, 327

K

K, see Potassium
K, stellar spectral type, 637
Kepler Crater, objective of robotic traverse, 402
Kr, see Krypton
KREEP, abundance in Balmer area, 168, 172; association with basalts in Marginis Basin, 168; availability in Smythii Basin, 170; basalt, 172, 669; basalt component, 171, 172, 365; definition, 168; distribution, 168; domination of trace-element patterns, 362; geological setting, 168; lunar resource, 170; volcanism, 172
Krypton, abundance in regolith, 393; laser, 203

L

Laboratories, lunar base, 676
Laboratory module, 476
LACE, 343; evidence for time-variation of lunar ^{40}Ar, 339; measurements of lunar neutral gases, 337-339
Lagrange point, 201, 643; laser station, 643; launch region for deep-space missions, 433; Venus, 642
Lander, Mars, 678, 679
Landing facility, lunar base, 140, 142, 151
Landing gear, 34, 47, 62
Landing site, Apollo, 668; Apollo 11, 186; Apollo 15, 158, 172; Apollo 17, 159, 194, 213, 227, 580; autolander, 179; crew lander, 179; development, 143; evaluation, 18; interaction with lander, 140; landing pad, 101, 123, 140, 151; radar transponders, 146; selection, 18, 209, 589
Large Magellanic Cloud, 321, 323
Laser, 69-71, 202, 203; cavity, 69, 639; coherence length, 639; communications, 27, 638; communications link, 637; diode, 212; energy, 69, 203; footprint from orbit, 203; frequency, 202, 203; fusion of lunar surface, 71; gain, 638, 639; gyro, 28; high pulse-repetition rate, 212; induced oscillation, 638; interstellar communications, 638; irradiation, 72; krypton, 203; lasing material, 212; lifetime, 209; LOLA, 212; Mars planetary, 639; mineral fluorescence, 203; natural carbon dioxide, 638; Nd-YAG, 212; optical radiation, 210; orbital altimetry, 209, 210, 212, 214; orbital resonator, 639; orbiting power station, 72; oscillator, 212; output, 203; photovoltaic converter, 69, 70, 72; planetary, 639, 641, 643; planetary design, 639; power output, 69-72; power requirement, 71, 72; power station, 69, 70; power transmission, 69, 70, 72, 73, 401; propulsion, 48, 54, 61, 66, 67, 70, 71, 73; pulse, 203, 210-212; radiation, 210; ranging system, 146, 210; receiver, 212; ring, 639; ring gyro technology, 126; ruby, 209; sensing capability in lunar surface systems, 606; shape of backscattered pulse, 210; solar-pumped, 69, 70; specific brightness, 638; specific power, 638; spectral linewidth, 638; stimulation of Raman emission, 201, 202; sustained oscillation, 639, 641; telemetry, 639, 641; thermal engine, 48; tracking, 212; transmission optics, 70; transmitter, 210; Venus planetary, 639; venusian interstellar transmitter, 639; wavelength, 203
Laser altimeter, 209, 210, 216; airborne, 209-213, 215; Apollo, 209, 211, 212; footprint, 210; lidar, 212; Lunar Observer, 209, 210, 216, 217; shuttle, 212
Laser backscatter waveform digitizer, 212
Launch facility, 133, 134
Launcher, mass driver, 397
Lava, basaltic, 412, 434; basaltic channel, terrestrial, 219; basaltic flows, 164, 219; buried flows in Balmer, 172; channels, 215, 216, 219, 220, 222; dated flows, 164; drainage from lava tube, 219; floor of Grimaldi, 157, 158; flow dynamics, 157; flow front, 212; flow sequence, Icelandic, 215; KREEP association, 168; lateral variations in Mare Smythii, 171; low viscosity, 215, 216; Mare Smythii, 164, 167, 171; pahoehoe, 219; physical characteristics, 219; sulfur-rich, 429; supply rate, 219
Lava flow, 212, 219, 225, 408; composition, 307; Mare Marginis, 171; Oceanus Procellarum, 160; terrestrial, 220
Lava tube, 219-228, 285, 287; application of inflatable structures, 289; base site, 220, 228, 281, 287-289, 408, 430, 433; earthquakes, 220; environmental conditions, 285; global distribution, 287; habitat site, 285, 288-

290, 302; illumination, 302; interior, 285, 287-289; moonquakes, 220; morphology, 287; morphometry, 220; origin, 285; penetration by impact, 220; potential shelters, 219; pressurized, 289; reconfiguration, 288, 289; relationship to sinuous rilles, 287; roof thicknesses, 287; shelter for superstructural elements, 285; solidity, 287; suitability for concrete processing, 289; terrestrial, 219, 220, 228, 287; waste disposal site, 228
Law, international, 247, 691-693; Roman, 692; space, 691-694
Law of the Sea Convention, 691
Lead, battery component, 431; removal from water by zeolites, 388; concentration in pyroclastic deposits, 170
Less Developed Countries, interpretation of Moon treaty, 692
Lettuce, 529, 538; composition, 525; part of adequate diet, 530; potential lunar base plant, 525; rapid growth, 297, 546; suitability for lunar biosphere, 297
Li, see Lithium
Libration, 163, 169, 170, 174, 176
Libration point, 31, 34, 35, 101, 102, 403, 404, 458
Life science, 476
Life support, 402, 647; advanced system, 557; Apollo portable system, 622; bioregenerative system, 547, 548, 556; electrical energy, 409; infrastructure element, 476; loss of oxygen from system, 549; lunar base capabilities, 518; lunar farm, 525, 529; material replacement, 549, 550; regenerative system, 554; requirements, 393, 395, 407, 472, 522, 525, 537, 549; solar energy, 409; space-based system, 550; space station system, 553; special-purpose minerals, 385, 387; system, 295, 296, 385, 518, 519, 522, 547, 548, 551; use of lunar materials, 385, 480, 547, 549, 550; water recycling system, 556
Life support system, portable, 178
Liquid oxygen (also see Oxygen), Earth-derived, 13-15, 454; fuel cell reactant, 403; lunar export, 135; lunar production, 51, 52, 146, 504, 604; lunar production module, 135, 136; lunar production plant, 14, 49, 102, 135, 402, 404, 453, 454, 506, 508, 509, 685-687; lunar-derived, 13, 14, 47, 49, 62, 63, 101, 103, 104, 107, 136, 206, 448, 450, 453-455, 457, 580; oxidizer, 13, 32, 34, 85, 119, 121, 128, 130, 133, 147, 181, 207, 432, 447, 449, 454, 455, 457, 677; pilot production plant, 14, 402, 508, 679; storage, 147; tank, 85, 87-89
Lithium, alloy with calcium, 427; heat-pipe fluid, 613; reducing agent, 427
Living quarters, 267; inflatable, 177; lava tube, 228; lunar base, 700; radiation protection, 177
LLOX, see Liquid oxygen
LM, see Lunar module
Logistics, 607; crew, 104; ECLS, 503, 504, 507-510; lunar base, 250, 480, 670, 685; lunar lander, 107; lunar support network, 686; module, 26, 400, 581; orbital depot, 92; space station, 123, 400; structure pressurization, 508
Loss tangent, 611
Low Earth orbit, 3-9, 12, 14, 15, 17, 18, 20, 23, 35, 36, 37, 39, 40-42, 44, 45, 47-49, 51, 52, 55, 56, 62, 64-67, 101, 102, 116, 119, 121, 123, 124, 133; assembly location for Mars vehicle, 680; atmospheric characteristics, 329; atomic oxygen, 301, 329, 332, 334; compared to lunar environment, 229, 334; debris environment, 329, 334, 660; escape velocity, 65; EVA, 603; fabrication of structures, 290; heavy lift vehicle payload capability, 593; industrial facility, 401; lander basing location, 102; maintenance facility, 66, 83; micrometeoroid environment, 330, 332, 334; nodal regression, 37; OTV base, 119; rendezvous, 42; retrieved satellite components, 332; servicing facility, 31, 34; space ferry, 450; space station, 25, 102, 119, 127, 133, 134, 164, 174, 450; space transportation node, 13, 17, 18, 31, 35, 36, 40, 42-44, 47, 52-58, 61-67, 78, 83-85, 101, 102, 116, 119, 120, 127, 128, 293, 133, 134, 136, 199, 200, 394, 399, 401, 402, 404, 405, 411, 448, 453, 456, 457, 593, 677-679, 700; staging facility, 61, 62, 66, 170; staging node, 681; storage location, 20, 55, 56, 61, 64; tether platform, 55, 65, 66, 67; use of lunar oxygen, 411
Low lunar orbit, 455; lunar lander base, 119; propellant depot, 133, 678, 679; space station, 53, 123, 133, 481; space transportation node, 35, 47, 48, 51, 61, 71, 102, 119, 199, 294, 453, 455-457, 678; transfer and servicing facility, 49
LRV, see Lunar roving vehicle
Luna 9, 161
Luna 13, 161
Luna 16, 190
Luna 20, 362
Luna 24, 190
Luna, lunar samples, 189, 330; missions, 189, 199, 307, 308, 361, 362, 380, 460, 469; program, 75
Lunar Atmospheric Composition Experiment, see LACE
Lunar colony, 685
Lunar community, 704; analogs, 704; challenges, 703; psychological support, 703; self-supporting, 697, 700; social support, 703
Lunar day, 169, 178, 593, 600; adapted crop cultivar, 522; duration, 580; heat flux variations at lunar south pole, 589; heat loss at lunar south pole, 591; heat rejection requirements, 582, 586; light pipes for plant illumination, 670; module air temperature control, 591; module heating, 581; negative heat flux, 584, 585, 589; polar lighting survey, 178; relationship to power availability, 421, 470, 478; solar energy supply, 613; surface temperature range, 387; temperature fluctuation, 136, 521, 580; thermal requirements, 149, 582
Lunar lander, 6, 25, 27, 28, 31, 32, 34, 47, 48, 51, 52, 55, 56, 61-65, 101-104, 116, 119-130, 140, 142, 143, 146, 148, 669; aerobrake, 123; Apollo, 116, 143; autonomy, 140; berthing in OTV, 34; cooling system, 149; crew, 124, 126-128, 179, 180; definition, 119; design, 116, 119, 123-125, 128, 151; docking, 126, 146; dust mobilization, 142, 145; Earth-storable, 125; energy storage, 593; engine, 34, 63, 64, 67, 113, 124, 141; expendable, 107, 109; flights, 103; guidance system, 146; life cycle, 125; logistics, 107; maintenance, 34, 52, 54, 123, 125, 128; mass, 52, 116, 119, 121-123, 128; modification of OTV, 62; modification, 137; multipurpose, 119, 125, 128-130; orbital basing, 102, 119, 123; payload, 34, 63, 67, 402; performance, 121; power, 148, 149; production costs, 130; propellant capacity, 130; propellant loading, 123; propellant storage, 119; propulsion, 28, 66, 124; radar, 144; RCS, 125; requirements, 101, 103, 104, 111-117, 124, 125; return to LEO, 123; reusable, 101, 102, 104-111, 119, 151; stage requirement, 101, 109, 116; stage, 101, 103, 111; surface stay time, 127; tether launch, 65; thrust chamber, 124
Lunar module, 119, 120, 133, 135, 136, 140, 143, 172, 180, 343, 620, 622; Apollo 17 impact, 185; ascent correlated with magnetosheath ion fluxes, 343; ascent stage, 120; base for Apollo EVA, 620, 622, 628; capacity, 184; components, 137; costs, 131; crew, 137; descent stage, 180, 333; design, 133, 134; dimensions, 134, 135; engine blast, 135; engine, 123, 124, 141; engineering, 131; factors in LRV deployment, 630, 631; flight frequency, 135; fueling, 137; landing, 135, 136; launch preparation, 137; loading operations, 136; LRV stowage, 621, 622, 627, 630; maintenance, 137; payload, 133, 120; power requirement, 127; propellant capacity, 134; rocket exhaust acceleration of lunar dust, 331, 332; safing, 137; servicing, 133; storage, 137; stowage of auxiliary LRV equipment, 631; surface transportation, 136, 137; transportation requirements, 135; unloading, 136
Lunar month, 123; polar lighting survey, 178
Lunar night, base power source, 148; cryogenic gas separation, 521, 615; Earthlight, 302; fuel cell reactant mass requirement, 595; influence on base power system, 29; laser altimeter operations, 212; lighting requirement for photosynthesis, 433, 670; neutral gas measurement by LACE, 338; module heat loss, 589, 591; power sources for VLFA, 326; surface operations, 136; temperature, 580; use of waste heat, 421
Lunar orbit, abort option, 125; communication satellite, 311, 327; fuel depot, 102; gamma-ray spectrometry, 156; inclination, 123; insertion maneuver, 119, 454; lunar laser altimeter, 210, 212; photography, 140; power satellite, 69, 72; propellant transfer, 123; remote sensing, 307, 312; rendezvous, 37, 42, 180; space station, 53, 123, 133, 481; space transportation infrastructure, 18; space transportation node, 6, 31, 34, 35, 36, 41, 47-49, 51, 61, 71, 101, 102, 104, 116, 119, 121, 123, 199, 294, 355, 448, 453, 455, 456, 457, 678; tether platform, 48; vehicle servicing facility, 32, 34, 49, 102, 104, 123, 209
Lunar Orbiter, data, 176; missions, 199; photography, 176, 178, 209, 210, 220, 221
Lunar Orbiter 3, 213
Lunar Orbiter 4, 176
Lunar roving vehicle, 178, 309, 311, 333, 619; advantages for lunar-surface operations, 620; antennas, 622; approval for development, 619; attitude indicator, 627; batteries, 622, 628, 629; crew station subsystem, 626, 627; deployment, 622-624, 630, 631; design, 619, 620, 622, 631; driving in reverse, 627; dust hazard, 622, 629; emergency driving mode, 624; evolution, 619; first use, 620; history, 619; insinuation into Apollo planning, 619; lighting requirements, 620; navigation system, 622, 627, 628; payload capacity, 620; potential for future use, 619, 631; speed indicator, 628; stability, 620; steering subsystem, 625; stowage in LM, 621, 627, 629, 630; testimonial, 632; thermal control system, 620, 629; turning radius, 625
Lunar surface transportation, 137, 143, 145, 245, 319, 325, 606-608; cargo, 634; constraints, 633; habitat modules, 134; infrastructure, 476; node, 102; power, 149; prefabricated modules, 261; regolith mining, 604; requirements, 604; surface preparation requirements, 478; vehicle, 143, 151, 604

Lunar surface transportation system, 133, 136, 334

M

Machine, boring, 409; compression testing, 484; continuous mining, 409; flexure testing, 485; tether repair, 58; tools, 397
Magma, basaltic, 219; chamber, 380; composition, 171, 366; crystallization, 379, 380; density, 381; electrolysis, 476, 519; global system, 168; injection below crater floors, 167; ocean, 167, 366, 379, 380; olivine flotation, 381; oxygen fugacity, 371; Stillwater Complex, 380, 381
Magnesium, armalcolite component, 370; availability in lunar soil, 520; basalt component, 362; basanite component, 380; distribution between ilmenite and silicates, 366; essential plant ion in lunar soil, 520; ilmenite component, 366, 370; metal, 424; olivine component, 206, 365; propellant, 433; pyroxene component, 206, 363, 365; reduction, 427; separation in magma ocean, 366; spinel component, 368
Magnet, costs in fusion reactor, 466; shielding in fusion reactor, 75, 77, 462, 466
Magnetic anomaly, intense, 173; Mare Marginis swirl field, 168, 171, 173; Reiner Gamma, 158; sources, 168
Magnetic field, fusion reactor, 461; gradient, 78; lunar, 173, 251, 660; martian, 660; pressure, 77; role in propulsion systems, 75; solar wind deflection, 173; surface measurements, 173
Magnetometer, 172, 173
Manganese, 408; ilmenite component, 366; olivine component, 365; source of soil acidity, 519
Manned lunar base, 17, 18, 47, 64, 83, 133, 155, 475, 503; development, 3; lava tube site, 219, 228; deployment option, 595; photovoltaic power system, 596; precursor missions, 199; site selection, 155; waste products, 228
Mantle, 167, 168, 174, 380; basalt source region, 171; boundary with crust, 173; composition of pyroclastics, 167; lunar xenoliths, 379, 380, 382; mascon source, 168; seismic velocity profile, 173; structure and thermal state, 173; terrestrial, 244
Manufacturing, 481; base for silicon solar cells, 595; cement, 483; cost, 411, 457; life-support requirements, 409; lunar, 65, 70, 283, 289, 397, 403, 472, 476, 480, 496, 647; lunar steel, 268; martian, 647; mass-delivery requirements, 479; module plant, 493, 494; orbital solar power plants, 450; repeatability, 97; requirements, 96, 100, 476, 477, 480, 481; space, 397, 399, 403, 405, 408, 657; system safety, 100; use of lunar regolith, 476
Map, albedo of Reiner Gamma, 158; color-difference of lunar nearside, 191, 193; crater density, 155; polar temperature, 178; titanium variation, 190; western Oceanus Procellarum, 160
Mare, Apollo sites, 171; basin margins and moonquakes, 232; craters, 213; dark, 362; effects on heat flow, 172; evolution, 160; Fe-FeS liquid segregation in magma, 429; helium abundance in regolith, 190, 477; helium-3 abundance with depth in regolith, 477; homogeneity of regolith, 477; ilmenite abundance, 429, 432; landforms, 212; landing sites, 362; lava, 155, 158, 164, 185; magma chambers, 380; materials, 157, 225, 227; mining sites, 189; plagioclase, 365; regolith, 171, 174, 187, 189, 190, 194, 195, 273, 469, 609, 613; relationship to dark-mantle deposits, 195; relationship to floor-fractured craters, 167; rilles, 219, 228; roughness, 185, 216; seismic velocity, 173; subsurface layering, 171; suitability for base site, 155; sulfur abundance, 429, 434, 443; surface boulder hazard, 185; terra boundaries, 168; thickness, 168; titanium content, 193; topography, 213
Mare basalt, 156, 159, 163, 164, 170, 185, 222, 225, 308, 362-366, 368, 370, 371, 380, 393, 411, 609; affinity to pyroclastics, 170, 171; Apollo 17, 194, 227; compositions, 164, 189, 412; fill of Neper Crater, 171; fill of Purkyne U Crater, 171; flows, 173; KREEPy, 171; related to mascons, 168; Tsiolkovsky Crater, 186, 187; thickness, 168;
Mare basins, 380
Mare Humorum, lava tubes, 227
Mare Imbrium, lava tubes, 227, 619
Mare Marginis, lava flows, 168, 171; swirl belt, 171, 173
Mare Serenitatis, dark mantle, 195; lava tubes, 222, 227
Mare Smythii, base site, 173, 174; astronomical observatory site, 170; basalts, 164, 170, 171; crater density, 164; heat flow, 168; ilmenite abundance, 170; pyroclastics, 170; radioactivity, 168; region, 168; regolith abundance, 170; soil chemistry, 170; topography, 170
Mare Tranquillitatis, helium-3 194; lava tubes, 222; regolith, 193; titanium content, 189-191
Maria, 156-158, 160, 164, 168, 189, 194; age and origin, 185; assumed uniformity, 193; asymmetry, 155; global distribution, 155; incomplete sampling, 190, 193, 195
Mars, aerocapture, 677; artificial satellite, 662; ascent stage, 678; atmosphere, 638, 660; base, 453, 475, 547, 550, 569, 571, 574, 667, 679, 681, 701; commercial utilization, 47; comparison to Antarctica, 243; difficulty of resupply, 660; effects of lunar liquid oxygen on missions, 457; environmental conditions, 244, 569, 573; exploration, 677, 678; gravitational environment, 571, 573, 574, 648, 650, 656, 657; habitat, 184, 393; human colony, 677; importer of lunar volatiles, 550; lack of magnetic field, 660, 661; lander, 455, 678-680; low orbit, 678; manned base, 453; manned missions, 83, 95, 96, 243, 244, 453, 457, 458, 677-681; mass-transfer system, 647, 649, 650; mesosphere, 638; micrometeoroid hazard, 660; mission, 29, 33, 62, 75, 78, 79, 84, 85, 453, 454, 456, 572, 574, 619, 660, 662; mission payload mass, 680; mission support, 83, 88, 90, 93, 687; mission vehicle, 678, 680; Moon as proving ground, 677-679, 681; multiple landings, 678; oblateness, 639; opposition, 453, 456; orbital eccentricity, 639; orbital laser, 639; oxygen production, 681; perihelion, 453; rotation period, 661; satellites, 411; size of manned vehicle, 660; space transportation, 453; stay time, 453, 455; temperatures, 660; use of lunar liquid oxygen, 453; vehicle, 84, 85, 88, 90, 454, 677, 678, 686; working environment, 661-663
Mars Observer, 210
Mascon, basin, 168, 173
Mass catcher, 397; libration point (L2), 403
Mass driver, 48, 61, 66, 67, 476; construction site, 170, 222; cost effectiveness, 67
Materials processing, 4, 63, 69, 70, 83, 177, 185, 337, 340, 353, 356, 399, 409, 559, 603, 604; space station, 83
Material utilization, lunar, 551
McMurdo Station, Antarctica, 245
Medicine, 476; lunar base mission, 475; relationship to occupational ergonomics, 659; space, 569
Megaregolith, 168, 173
Mercury (element), hazard, 301
Mercury (planet), 667; atmosphere, 217; orbit, 638
Meteorite, component in lunar regolith, 361; generation of impact melts, 370; hydrated, 183; impact, 75, 287; impact-generated seismic shaking, 220; impact mixing of lunar soil, 373, 469; impact protection, 287; impact pulverization of regolith, 609; impact volatilization, 183; iron, 213; shield for optics, 300; shock metamorphism, 361, 362, 371, 519; source of lunar erosion, 361
Methane, 407, 432; by-product of helium mining, 475; component of complex organic compounds, 550; energy source, 675; flame, 654, 656; possible regolith volatile, 610; product of anaerobic decomposition, 675; relationship to lunar transient phenomena, 408; removal from atmosphere by biological systems, 517; source of hydrogen, 519, 521; use in ilmenite reduction, 521; waste, 432
Mg, see Magnesium
Microprobe, 483
Microscope, optical, 487; scanning electron, 483, 487
Microwave, 212; communications, 27; energy input into regolith, 612, 614; extraction of hydrogen from regolith, 407; field attenuation, 611; frequency, 612; generation from electricity, 614; observation of lunar roughness, 211; orbital altimeter, 210; penetration of regolith, 611; potential role in processing lunar materials, 611; radiation coupling with material, 611; radiometer, 211; use in producing plasma, 559
Mineral, beneficiation, 613; breccia components, 362; cation exchange capacity, 389; comminution, 409; composition related to hydrogen content, 437; conditions of formation, 361; crystallization temperature, 361; deposition by crystal settling, 379; deposits, 199; dissolution, 519; excess in tissue due to skeletal bone loss, 569; extraction, 409; extraction and processing, 408; extraction of oxygen with fluorine, 423; flow during mining, 613; fluorination, 423, 426; fragments in agglutinates, 361, 372, 385; hydrothermal concentrations, 379; imbalances in human body due to zero g, 569; lack of chemical weathering on Moon, 519; laser-induced fluorescence, 203; loss from bone, 569, 570, 661; lunar resources, 518; mining, 613; ore, 159, 379; processing, 408, 409, 423, 609, 613; reduction processes, 409; regolith beneficiation, 611; remote sensing, 199; source of plant-growth anions, 387; terrestrial resources, 244, 245
Mining, activities as seismic sources, 172, 185; automated, 409, 604, 609; by-products, 472, 479; candidate methodologies, 409; centralized, 408, 478, 479; considerations, 195; continuous, 409; cost, 289, 411, 471, 550; depth, 194, 470; equipment transportation, 411; equivalence to terrestrial strip mining, 241, 613; hardware delivery, 479; helium, 80, 170, 174, 183-185, 189, 347, 394, 471, 475, 477-482, 547; hydrogen, 393, 437, 444; ilmenite, 170, 521, 522; in situ, 611, 612; incompatibility

with observatories, 183, 185, 186, 327, 329; lunar, 18, 72, 184, 283, 289, 319, 349, 407-409, 423, 478, 543; lunar incentives, 470; lunar ore bodies, 408; lunar oxygen, 85; lunar sulfur, 430; mobile, 471, 612, 613, 616; mobile and centralized concepts compared, 478-480; modification of lunar atmosphere, 184, 186, 341, 347, 349, 350; nitrogen; nuclear energy requirement, 409; objectives, 616; open pit, 611, 612; operations, 194, 408, 409, 476, 607, 609; pattern, 194; phosphorus, 521; potential sites, 189, 194, 195, 469, 609, 613; rate of helium-3 recovery, 610; regolith, 170, 408, 547, 549, 604, 607; relevant factors, 189; required amount for helium production, 189; required area, 612; requirements, 194; resources, 163, 643; scars, 434; sieving operations, 395; simplicity of shallow excavation, 434; small bodies, 411; suitable areas, 189, 195; strategies, 611; terrestrial standards, 395; terrestrial systems, 407, 409; underground, 408, 409; waste disposal, 228

Mir, effects of prolonged exposure to microgravity, 353, 668; space station, 237, 353, 569, 570

Mirror, adjustment as array component, 641; diffraction grating, 642; laser transmission, 69; magnetic, 77, 78; reactor, 75, 462

Mission planning, Apollo, 620; lunar surface, 143, 146; Mars, 457

Mn, see Manganese

Mobility, aids for working in space, 662; inflatable structures, 289; mobile mining system, 613; module, 607; platform, 607; regolith excavator, 613; SKITTER systems, 634; spacesuit, 662, 663, 668

Module, aerocapture, 678; agricultural, 297, 522; burial, 590, 604, 669; CELSS, 300-303; command, 179, 180, 209, 485; concrete construction, 496; concrete prestressing, 494; concrete structural, 493; construction, 493, 496; crew, 18, 34, 121, 127, 128; electric propulsion, 39; floor area, 493; frame, 494, 496; greenhouse, 522, 556; habitat, 18, 27, 177, 179, 250, 255, 493, 507, 508, 580, 597, 604, 669, 678; heat load, 581, 582, 590, 591; heat generating, 297; interfaces, 669; interior, 26, 496; interior contamination with dust, 669; laboratory, 23, 476, 580, 590; liquid oxygen production, 135; logistics, 26, 400, 581; lunar base, 255-259, 261-264, 266, 293-295, 297, 517; manned, 9, 13, 21, 42; manufacturing plant, 493, 494; Mars lander habitation, 679; mass, 494; mobile miner, 613; navigation, 607; passive thermal control, 589; planetary habitation, 679; power, 668; pressurization, 493; propulsion, 200; regolith shielding, 581, 589; space station, 249, 251, 504, 506, 507, 509; storage, 667, 670; subsurface, 298; support, 400; transport, 667, 670; unshielded, 581, 590

Moon Park, CELSS simulator, 673, 674; description, 673; lunar base demonstrator, 676

Moon Treaty, 691-694; "common heritage of mankind" provision, 691, 692, 693; full title, 691; goals, 694; interpretation of US government, 692; interpretive confusion with Outer Space Treaty, 693; limitation of "common heritage" provision, 693; negotiations, 692; number of ratifications compared to Sea Treaty, 693

Moonquake, effect on lunar base, 231; ground motion, 233; largest recorded, 268; seismic energy, 232; shallow, 173, 231-233

Muscle, atrophy prevention by centrifuge therapy, 355; effects of reduced gravity, 353, 571, 661, 662; relationship of mass loss to loss of strength, 662

N

N, see Nitrogen

Na, see Sodium,

Navigation, 20, 25, 28, 125, 140, 144, 146; Apollo LRV system, 620, 622, 624, 627, 628, 630; autonomous, 606; beacon, 146, 178-180; error, 135, 143, 145; inertial, 141; landing, 126, 141; lunar base support, 139; module, 607; remote aids, 143; system, 34, 136, 139, 140, 144; terrain-following, 126; visual, 33, 141

Nb, see Niobium

Ne, see Neon

Neon, abundance in regolith, 184, 393; detection during lunar night, 338; lunar thermal escape constant, 339

Neutral particle, injection into lunar atmosphere, 348

Neutrino, emissions from supernovae, 318; lunar detector, 317; observatories, 318

Neutron, 76, 462, 468; damage, 462, 468, 473; exposure testing facility, 468; fusion reaction production, 459-462, 466, 475; fluence, 79, 80; probe monitoring of soil moisture, 520; shielding, 461; wall loading, 462, 466

Neutron star, 318

NH_3, see Ammonia

Ni, see Nickel

Nickel, 412; basalt component, 216; battery component, 28, 29, 180; content of native Fe metal, 371; heavy metal in lunar soil, 520; kamacite component, 371; lunar-derived, 408; olivine component, 365; schreibersite component, 370; storage container for fluorine, 423, 424; taenite component, 371

Niobium, rutile component, 370

Nitrogen, 560; abundance in regolith, 393, 430, 550; ammonia source, 552; atmosphere supply, 126; bacteria, 547; by-product of helium production, 470, 475, 548; component of spacesuit atmosphere, 660; concentration in anaerobic digestion effluent, 521; correlation of abundance with soil maturity, 437; effects on flames in microgravity, 655; effects on strength of concrete, 487; helium as partial substitute in lunar base atmosphere, 548; fixing microorganisms, 532; flow through CELSS, 525, 528; logistics for ECLS, 504, 508; loss from base, 509; lunar abundance, 394, 395, 429, 433; lunar-derived, 547, 668; mineral processing reagent, 423; mineralization by heterotrophic microorganisms, 520; mining, 394; plant nutrient, 296, 520, 553, 556; pressurization gas, 508, 509, 547, 548, 550; production by anaerobic digestion of biomass, 521; pyrolitic extraction from regolith, 394; reduction by algae, 520; replacement requirement, 548, 549; requirement for habitat atmosphere, 508; requirement for self-sufficient lunar base, 547; solar wind as source, 373, 411, 421, 609; supply to Moon from Earth, 504, 509; use in regenerative life-support systems, 177; zeolite-column separation, 388

Noble gas, concentrations in breccias, 440; correlation of abundance with agglutinates, 440

Norite, anorthositic, 418; highland component, 362; layered intrusive complex, 379; magnesian, 418; olivine content, 365

Nuclear energy, reactors, 459; helium-3 fuel, 361, 374, 481; laser pumping, 638; power source for lunar base, 389

Nuclear fusion, 79-81; advantages of deuterium-helium-3 over deuterium-tritium reactions, 475; breakeven, 459; comparison between deuterium-tritium and deuterium-helium-3, 466; controlled reaction, 459; conventional cycle, 667; cost of power plants, 473; description of cycle, 460; deuterium-helium-3 fusion cycle, 481; deuterium-helium-3 plants, 466, 472; deuterium-helium-3 plasma, 462; deuterium-helium-3 reaction, 459, 460, 464, 475, 477; deuterium-helium-3 reactor, 460, 463, 466; deuterium-tritium reaction, 459; efficiency of electrical production, 466; energy, 75, 76, 79; energy conversion to electricity, 76; experimentation, 459; fuel, 75; fuel cycle, 75, 81; helium-3 fuel, 184, 187, 189, 277, 349, 373, 394, 475, 482, 547, 549, 550, 609, 667; influence on economic factors, 462; physics, 79; power, 75, 76, 79-81, 459-461, 481, 609; power, development, 75, 79, 80; power, fuel, 81; power plant, 395, 463, 466, 610; power sources in space, 459; products, 75, 609; propulsion, 75-81, 481; quantitative advantage relative to fission, 466; radiation damage to reactor equipment, 464, 465; rarity of terrestrial helium-3, 475, 477, 482; reaction rates for various fuels, 460; reactor, 75, 76, 79, 170, 466-468, 473, 609; safety risk, 463, 482, space applications, 79, 81; stellar reaction, 459; sustainability with terrestrial helium-3, 609; terrestrial, 475; timetable, 472

Nuclear power, 29, 48, 246; electrical source for regolith-heating microwaves, 614; facility, 134; integration with ECLS, 505; reliability, 464; safety issues, 67, 482; SP-100 system, 593, 594; terrestrial, 482; tunneling device, 294; use in Antarctica, 176; use in water reclamation systems, 505; usefulness at lunar polar base, 176

Nuclear propulsion, 54

Nutrition, plant, 541

O

O, see Oxygen

O_2, see Oxygen

Olivine, 365

One-sixth gravity, 470, 613, 648; centrifuge therapy for deconditioning, 355; effect on compressive strength of mortar, 489; factor in lunar solar-array design, 594; KC-135 aircraft simulation, 655; lunar centrifuge, 356; neurovestibular adaptation, 353; physiological effects, 353, 354, 572, 574

Optical astronomy, incompatible lunar operations, 327; lunar, 325

Orbital maneuvering vehicle, 17, 85, 400

Orbital station, variable-gravity facility, 661

Orbital transfer, stage, 31; staging facility, 61

Orbital transfer vehicle, 3, 6-9, 13, 17, 18, 23, 25, 32, 34, 35-43, 47, 48, 51, 52, 55, 56, 61-67, 69, 70, 99, 119, 123, 133, 397, 399-401, 437, 678; aerobrake, 9, 12, 34, 36, 47, 62, 65, 119; arcjet propulsion, 39; automated, 64, 126, 128; avionics, 62; basic lunar-lander vehicle, 61-63, 402;

chemical propulsion, 36-42, 65; configuration, 64; depot, 95, 99; design, 37-39, 62; docking, 37, 99; electric propulsion, 37-44; engine, 37, 62, 63, 66, 67, 124, 125; expendable, 6, 9, 11, 12; fleet size, 42-44; fueling, 98; gas source, 99; gravity-gradient stabilization, 37; kinetic energy, 66; laser propulsion, 48, 66, 67; lunar lander ferry, 119, 123, 128; magnetoplasma-dynamic propulsion, 39, 42, 44; maneuvering capability, 36, 57; mass, 6-9, 37-43, 51, 56, 65; mission frequency, 48; modular, 3, 9; momentum, 55, 65; nuclear-electric propulsion, 37, 43, 48; one-stage, 12, 15, 34; one- vs. two-stage, 9; orbital assembly, 18; orbital facility, 63, 66, 95, 399, 400; payload, 39, 43, 44, 56, 64; propellant, 34, 56, 63, 64, 128; propulsion system, 22, 34, 35, 37-39, 62, 63, 124; rendezvous, 36; reusable vs. expendable, 9; reusable, 13, 15, 678; servicing, 37; size, 43, 44; solar-electric propulsion, 37-39, 43; tether propulsion, 48, 55-57, 65, 66; transportation system, 123; two-stage, 6, 12, 15, 44, 119

Orbiter, communications relay, 179; lunar, 401; Lunar Geoscience, 209, 210; lunar polar imaging, 178, 209; space shuttle, 21, 32, 127, 247

Ore, deposit, 199, 308, 379, 382, 615; detection by remote sensing, 380; extraction, 408; ilmenite, 159, 670; lunar grades, 393, 670; lunar helium, 615; lunar mineral deposits, 379; mining, 408; profit implication, 379; sulfur-rich, 429

Organic material, conversion to gaseous products, 559

NASA organizational structure, current, 683, 687, 688; difficulty in developing efficiency, 687; during Apollo, 688; lines of authority, 688; necessity for revision, 683; recommendation, 683, 688; review before adoption, 689; traditional, 683

Outcrop, hazards to geologists, 309

Outer Space Treaty, 693, 694; "province of all mankind" provision, 692-694; absence of "common heritage of mankind" provision, 692; acceptance, 693; character in international law, 693; common ground for US and USSR, 694; full title, 691; international agreement, 691; international confusion, 692; lack of rules for acceptance, 691; objection of US government, 692; quasiconstitutional function, 692; ratification, 693; reaction of factions in US space community, 694; similarity of US and USSR concepts, 691; strengthening, 693; US interpretation, 694

Outpost, automated astronomical, 169, 174; CELSS, 674; communications, 170, 171, 174; crew, 675, 676; lunar, 3, 18, 450, 678, 679; water, 674, 676

Oxygen, aerobic microbial process, 647; anorthosite source, 170, 408; atmospheric supply, 126; atomic, 329, 332, 334, 342; boiloff rate, 39; capture in electrolytic reactions, 421; component of habitat atmosphere, 433; component of spacesuit atmosphere, 660; computer monitoring in Biosphere II, 517; cycle in lunar base, 519; demand by plants, 542; diffusion in burning process, 653, 655; Earth-derived, 411; ECLS recovery, 504-508; effect on flame, 655; electrode catalyst in regenerative fuel cell, 595; electrolytic production, 411-421, 504, 562; exchange reaction with fluorine, 424, 425; explosion, 95; extraction from lunar materials, 64, 366-368, 379, 394, 412, 423-427, 437, 472, 479, 496, 518, 519; flow through CELSS, 525; fluxes during crop growth, 528; fraction of lunar surface by mass, 393; fuel-cell reactant, 126, 127, 246, 404, 593, 595, 668; fugacity, 361, 362, 366, 371, 412; gamma-ray spectral lines, 190; gaseous, 63, 125; generator in CELSS, 675; handling by ECLS, 507; hazard, 98, 99; human consumption during work, 662; ilmenite as source, 64, 155, 159, 160, 170, 184, 366, 367, 379, 408, 429, 432, 521, 549, 668; imported by base from Earth, 509; ion accelerated by solar wind, 347; losses, 506-508, 549; lunar abundance, 393, 394, 411, 429; lunar atmospheric scale height, 349; lunar export to space station, 670; lunar mining, 423; lunar resource, 155, 206, 361; lunar-derived, 3, 4, 13, 15, 18, 47, 48, 55, 61-64, 66, 67, 85, 121, 124, 184, 199, 207, 361, 379, 394, 399, 402, 404, 411, 447, 450, 453, 481, 521, 549, 580, 668, 670, 677-679, 681, 700; Mars-derived, 681; mass flux during crop life cycle, 525; model lunar atmosphere, 342; monatomic, 301; NaOH source, 432; obtained from cometary nucleus, 342; olivine as source, 427; orbital storage, 95, 99; other bodies as sources, 411; outgassing of molecular, 349; oxidizer, 6, 17, 28, 35-42, 44, 45, 47, 55, 56, 57, 62-65, 85, 102, 123, 124, 133, 134, 136, 137, 148, 180, 206, 207, 400, 407, 411, 432, 433, 479; Phobos-derived, 678, 681; pilot production plant, 47, 472, 679; polar ice source, 411; production, 18, 20, 35, 67, 170, 174, 181, 184, 206, 366, 368, 424, 432, 434, 453, 457, 472, 475, 476, 546, 551, 562, 604, 667, 673, 674, 675, 700; production plant 47, 48, 53, 55, 64, 72, 404, 432, 668, 679, 681; production by plants, 528, 537, 543, 549, 556; production cost, 457; propellant, 66; pyroclastics as source, 228; pyroxene as source, 408, 427; rate of usage, 394; recycling, 551; regolith sources, 374, 387, 407, 421, 432, 434; removal from organic compounds, 432; required for base operations, 408, 508; requirement of life-support system, 549; requirement of waste-management processes, 542; separation by zeolites, 385, 388; shuttle external tank as source, 398; solubility in silicate melts, 412; spacesuit atmosphere, 660; storage, 62, 64, 136, 137, 180, 542; supply to plant roots, 538; tank, 127, 128, 207; turbopump, 63; types of reactions with fluorine, 424; ulvospinel reduction product, 368; use in regenerative life-support systems, 177; vaporization of lunar soil, 342; waste conversion in plasma reactor, 560, 561; wastes as source, 521; water as source, 432; working fluid in metal-fueled rocket, 433; yield on Moon from a 1-kt nuclear device, 342

Ozone, absorption of solar ultraviolet radiation, 244; stratospheric, 244; water disinfectant, 553

P

P, see Phosphorus

Palladium, use in hydrogen separation, 615, 616

Parking, Apollo LRV, 625

Parking orbit, 101, 119; altitude, 121; elliptical martian, 455; inclination, 123; low Earth, 179

Pathfinder, 18

Payload, HLV requirement, 180

Pb, see Lead

Pd, see Palladium

Petrology, lunar samples, 361

Phase equilibria, lunar compared to terrestrial, 379

Phobos, 680; low gravity, 662, 663; manned mission, 453, 678, 679; oxygen production, 678, 681; resource potential, 393, 411, 678

Phosphorus, abundance in regolith, 393; KREEP component, 362; mineralization by heterotrophic microorganisms, 520; mining, 521; plant nutrient, 296; possible deficiency in lunar soil for plant growth, 520; production by anaerobic digestion of biomass, 521; requirement for plant growth, 553, 556; use in lunar agriculture, 170; wastes as source, 521

Photovoltaic array, 28, 594, 602; description, 594; efficiency defined, 593; power per unit mass, 594, 595, 597; technology, 594

Photovoltaic power system, 593, 596

Physics, atmosphere containment, 282; deuterium-helium-3 fusion reaction, 460, 462, 464; deuterium-tritium ignition, 468; fluid phenomena in reduced gravity, 655; fusion, 75, 79; materials, 468; plasma, 79, 468, 473; pressure vessel, 283, 285; protostellar collapse, 316; star formation, 319; supernova, 318

Physiology, human in 1/6-g, 670; potato, 543; relationship to occupational ergonomics, 659

Plagioclase, 167

Planetary exploration, 673, 681, 688

Planetary science, 309, 679

Plant (biological), anaerobically digested biomass as soil conditioner, 520; areal requirements, 534, 546; artificial lighting for growth, 518; biomass in Biosphere II, 514; canopy, 541, 546; capillary support, 539; carbon dioxide production, 549; correlation of yield and pH, 520; cultivation in Biosphere II, 516; edible vegetable, 674, 675; effects of ethylene as hormone, 532; effects of rhizosphere microbes on growth, 532; factors affecting productivity, 543, 544; factors in growth, 537; fertility enhancement with zeolites, 388; food, 531; food source for tilapia, 521; growth, 301, 302, 385, 387-389, 470, 532, 538; growing facilities at lunar base, 547; growth in controlled environment, 543; growth module, 556; growth system, 553; growth tests in Biosphere II Test Module, 516; hydroponic growing system, 519, 520, 674; loss of carbon, 531; microbial community, 531-533; nutrient delivery system, 538, 539, 542; nutrients, 533, 538, 539, 542, 544; oxygen supply to roots, 538; pathogen, 531, 532, 536; photosynthate, 520; protein, 525; production with zeoponics, 388; proper combinations, 296, 297; root exudation as source of soil acidity, 519; roots, 520, 531, 532; simulated regolith as growth medium, 675; soil as root support, 533; spacing, 538, 546; species in CELSS, 544; species origins in Biosphere II, 514; stress, 522; substrates for growth, 389; sugars, 432; thigmomorphogenesis, 535; tissue culture, 516; transpiration of water, 521; use of solar radiation in CELSS, 544; yields in lunar lighting cycles, 518; zeolite substrates, 388

Plant (factory), agricultural, 669, 670; CELSS species list, 534; cement, 494; Chernobyl, 464; fusion power, 395, 461-469, 472, 481, 609-611, 613; fusion power demonstrator, 469; lunar central power, 470, 476, 481; lunar concrete, 268; lunar propellant, 454; mobile nuclear power, 470; pilot lunar oxygen, 14, 47, 472, 679; mobile regolith processing, 434; module manufacturing, 493-495; nuclear power, 48, 176, 464, 465, 614; oxygen production, 47, 48, 53, 64, 72, 402, 404, 432, 453, 506, 508, 509, 549, 674, 675, 679, 681; prestressed material, 494; regolith

mining, 670; regolith processing, 395, 611, 613; thermal energy required for sulfur production, 434
Plasma, 35, 36, 76-80; charge imbalance at lunar surface, 340; cloud, 348; collective effects on neutral-gas transport, 341, 343, 348; current, 80; defined, 559; deuterium-helium-3, 460-462; deuterium-tritium, 461, 468; dielectric constant, 348; extralunar origin, 340; generation, 559, 560; hydrogen, 48, 562; interactions with large gas releases, 343; lunar, 337, 339, 344, 349; physics, 468, 473; pressure, 77; magnetized, 348; oxygen conversion unit, 561; reactor, 559-562; shielding, 347-350; temperature, 77-79, 461; terrestrial magnetospheric, 339, 340; thermalized solar wind, 340; waste conversion, 560
Platinum, use in electrolysis, 416, 418; lunar-derived, 408; reactivity with fluorine, 427; use in resistance measurements of silicate melts, 413
Polar base, lunar, 178, 181
Polar orbit, lunar, 102, 103, 178, 179, 200, 205, 209
Polarization, electric field of solar wind, 348; estimate of ilmenite content, 159, 160; infrared observations of interstellar gas clouds, 318; high-density regolith, 158; silicate melt in electrolytic cell, 414, 415
Population density, 238
Porosity, concrete, 490; regolith, 158, 273, 395, 487; regolith particles, 483
Potassium, 167; abundance in lunar pyroclastic coating, 430; basalt component, 170, 362; feldspar, 365; hydroxide electrolyte, 629; KREEP component, 362; lunar atmospheric component, 338, 339; lunar resource, 227; plant nutrient, 296, 520; potential lunar sources, 669; production by anaerobic digestion of biomass, 521; sites in smectites, 389; source of ^{40}Ar, 339; vitamin, 531; zeolite component, 386
Potato, 525, 526, 529, 530, 543, 546; Biosphere II, 516; calorie content, 544; carbohydrate content, 529; composition of edible portion, 525; factors in production, 543; growth curve, 526; information base, 543; Irish, 543; manipulation of growing environment, 543, 544; suitability for CELSS, 525, 543, 544; white, 538
Power lifter, bone mineral content, 571
Power plant, 18, 670; fusion, 395, 461-463, 465, 466, 469, 481, 610, 611, 613; helium-4 working fluid, 470; lunar, 470, 476, 481, 494; mobile nuclear, 470; nuclear, 464
Power requirement, electrolytic cell, 411, 418, 419; lunar lander, 127; lunar oxygen-production plant, 404; space station, 23
Power station, lunar orbiting, 69; orbiting solar laser, 69-71
Power system, Antarctic, 246; ECLS, 505; excavator, 72; fuel cell, 670; laser, 69, 70; lunar base, 126, 148, 181, 505, 593-596; lunar lander, 127, 128; orbital transfer vehicle, 39, 41-43; roving vehicle, 70; solar, 62, 181; space station, 28, 29, 504; tether platform, 57; waste heat production, 505
Power transmission, laser, 69, 70, 73
Private enterprise, interpreted inhibition by Outer Space Treaty, 692, 693; apparent incompatibility with Outer Space Treaty, 692, 693
Private sector economy, early American colony, 697; early Australian colony, 697; first step at lunar base, 700; growth at lunar base, 698, 700
Probe, heat flow, 172; imaging impact, 178; soil moisture, 520
Procellarum region, 189
Processing, biological, 559; biomass, 246, 537, 538; cargo, 136; central gas facility, 615, 616; central lunar facility, 478, 482; central station, 185; chemical, 398, 405; closed loop, 559; composite fabrication, 398; concrete, 289, 497; data, 26, 27, 323, 643; edible crops, 522; fission fuel, 81; food, 245, 547-549; hazardous systems, 20; high-vacuum materials, 341, 347; human waste, 563; humidity condensate, 504, 506; inertial measurement unit, 126; in situ materials, 245; lander data system, 125, 126; microbial, 407; mineral, 408, 409, 609, 613; orbital, 17, 20-23; oxygen, 546; refinement of lunar-derived gases, 478; regolith, 184, 194, 195, 395, 409, 429, 475-477, 521, 604, 609, 611-614; remote-sensing data, 199; resource, 409, 476, 479; signal, 409, 626, 628, 643; solid waste, 505; space shuttle, 32, 603; sulfur, 433, 434; terrestrial iron techniques, 405; vehicle, 83, 91, 93; waste, 506, 507, 552, 559, 561, 563; waste water, 506, 508, 597
Project Apollo, 237
Propellant, 54, 55, 57, 58, 63, 67, 79, 88, 89, 92, 116, 119-125, 133, 136, 205, 206; argon, 66; boiloff, 39, 40, 453; contamination, 84; cryogenic, 85, 120, 180; density, 120, 124, 130; Earth-storable, 124; fraction of rocket mass, 449; fusion propulsion, 79; handling, 62, 89; hazard, 84-87, 89, 90, 95, 99; hydrazine, 85; hydrogen, 47, 55, 64, 66, 71, 181, 206, 394, 402, 432, 455, 481; hypergolic, 180; leakage, 99; loading, 91, 119, 123, 130; lunar lander capacity, 121, 130, 134; lunar lander combinations, 124; lunar lander mass, 56; lunar mission requirements, 101, 113; lunar plant, 453, 454; lunar production, 206, 356 408, 447, 448, 457; lunar sources, 206; lunar-derived, 65-67, 206, 308, 341, 402, 453, 454, 475, 481, 549, 700; magnetoplasmadynamic thruster, 40; orbital storage, 18, 31, 32, 83, 85, 92, 93, 95, 96, 102, 133, 448, 450, 678, 679; orbital transfer vehicle, 6, 9, 35, 36, 39-44, 56, 62, 64; Phobos-derived, 678; protection from impact, 84; pumping, 93; RCS, 37, 125; requirement for orbit maintenance, 204, 205; rescue mission requirement, 85; robotic handling, 84; savings by aerocapture, 677; savings by landing beacons, 668; savings by tether system, 57; scavenging, 400; spillage, 93; storage, 20, 25, 45, 47, 62, 84, 85, 88, 95, 100, 120, 125, 133, 136; sulfur, 228; supercritical, 39; tank, 6, 9, 18, 33, 34, 39, 84-89, 91, 93, 111-116, 125, 127, 128, 134, 136, 137, 147, 180, 296; tether platform, 58; thermal protection, 84; transfer, 34, 62, 63, 84, 95, 123, 147, 148, 678; unburned, 180; unloading system, 133, 136; unprocessed regolith, 407; zero-gravity transfer, 102; xenon, 39, 40, 48, 642
Propulsion, advanced technology, 47, 61, 66, 124; Apollo systems, 124; arcjet, 39, 44; chemical, 35-37, 41, 42, 44, 47, 54, 65, 78; electric, 35-39, 42, 44, 45, 56, 401; failure during lunar descent, 180; high specific impulse, 35, 65, 66; hydrogen based, 444; ion, 35-39, 44, 48, 66, 67; ion electric, 37; laser, 48, 54, 61, 66, 67, 69, 70, 71, 73; lunar lander, 34, 124; lunar lander requirements, 111; magnetoplasmadynamic, 35, 36, 39, 44; module, 200; N_2O_4/MMH system, 125; nuclear, 54; nuclear electric, 37; nuclear fusion, 75-81; OTV, 34, 22, 37; oxygen/hydrogen, 35, 133; pressure-fed system, 124; pump-fed systems, 124; requirement for L1 platform, 102; reusable system, 20; RL-10 system, 113; xenon-ion, 642
Propulsion system, 124, 179, 180, 199-201, 681; chemical, 447, 448, 677; fusion, 75, 76, 78, 79; libration point platform, 102; lunar ascent vehicle, 113; lunar lander, 28, 111, 113, 116, 124, 125; Mars transfer vehicle, 455; mass-driver packet, 48; OTV, 22, 37-40, 56, 67; pump-fed, 124; tether, 55
Prospecting, lunar, 401, 408; roving vehicle, 73; volatiles, 176
Prospector, lunar orbital, 199
Proton, 80, 240; launch vehicle, 400; release in biological target, 433
"Province of all mankind" provision, concept in international space law, 691; interpretation of less-developed countries, 692; interpretation of US government, 692, 694; interpretation of USSR government, 692; objection of US government, 692; political meaning, 692, 693; provision of Outer Space Treaty, 692-694; support by US and USSR space programs, 693
Pt, see Platinum
Pyroclastic, material, 167, 171, 225-228, 431, 434; lunar glass, 167, 170, 190, 195, 429; lunar particles and volatiles, 431, 432, 434; metal sulfides in soils, 429; role of sulfur in eruptions, 429; vapor-transported elements, 430
Pyroclastic debris, use in constructing bricks, 228
Pyroxferroite, 365

Q

Quarantine, 241

R

Radar altimeter, 141, 176, 209, 210; Apollo 17, 209; backscatter, 204; bistatic, 209; broad-beam system, 210; Earth-based, 209, 211, 217; energy, 203; lunar lander, 144; lunar-surface based, 126, 228; navigation transponder, 140, 146; pulse, 204, 210; reflectance of dark-mantle material, 195; reflection, 203; signal propagation, 203; sounding, 203, 204; subsurface mapper, 201, 203; support of Apollo landings, 141; survey, 189, 195; synthetic aperture, 204; terrain-following, 126; transmitter antenna, 210
Radiation, 90; background, 251; base-generated impediment to astronomy, 325; bremsstrahlung, 316; cascading in regolith, 330; concrete shield, 499; cosmic, 329, 333; damage, solar cell, 39; damage, tether, 58; damage and sulphyldryl prophylaxis, 433; darkening of equipment surfaces, 333; degradation, solar array, 39; effects on power-plant reliability, 464; effects on Surveyor 3, 331, 333; electromagnetic, 253; electromagnetic generation of plasma, 559, 560; erosion of habitat integrity, 251; filter, 300, 302; fission reactor containment, 466; galactic, 251, 252, 261, 266, 329; habitat protection, 250, 251, 275, 293; hazard, 70, 72, 136, 171, 251, 275, 294, 296, 603, 606, 659; heat dissipation mechanism, 615, 629; ionizing, 275, 433, 659; impediments to astronomy, 334; laser, 210; lava tube roof as shielding, 220, 228, 287; low Earth orbit environment, 332; lunar environment, 251, 282, 325; magnetic field shield, 173; magnetic resonance imaging, 661; material sensitivity, 99, 251, 253; microwave, 611; nonionizing, 659; photosynthetically active, 539, 544; pressure, 90; process in combustion, 654-656; propulsion system reactor,

37-39; protection, 89, 90, 134, 261; reactor damage, 461, 462, 464-466; regolith shielding, 170, 247, 268, 302, 385, 408, 433, 522, 580, 604; relative immunity of robotic field geologist, 309; resistance of lunar concrete, 389; sensitivity of crops, 670; shielding, 48, 92, 93, 240, 252, 253, 255, 259, 261, 266, 274, 275, 279, 281, 282, 285, 288, 663; shielding requirement at geosynchronous altitude, 239; solar, 99, 297; solar effects on astronomical equipment, 329, 332; solar energetic particle events, 251, 261; solar ionization of neutral gas, 347; solar optical filters, 302, 303; spacecraft shielding, 659; structural complications due to shielding, 282; sulphydryl compounds for human protection, 433; synchrotron, 461; thermal, 76, 78, 79, 136, 329; threat to electronics, 136; ultraviolet, 244; ultraviolet degradation of optical coatings, 334; ultraviolet sterilization of solid waste, 675; use in gamma-ray spectroscopy, 190; Van Allen belt, 39; waste heat, 399, 421, 433; X-ray background, 317

Radiation leakage, nuclear power plant, 176

Radio, aid to lunar-surface navigation, 311; constant contact with teleoperated robot, 311; dish antennas, 315; Earth-based astrometry, 321; Earth-Moon round trip time, 309; interference of lunar ionosphere with observations, 349; interferometer, 315-317, 319, 321, 323; low-frequency array, 319; quiet lunar environment, 315; superheterodyne detector, 321; very low frequency astronomy, 319, 349

Radio astrometry, 321; accuracy limited by water vapor, 321; lunar, 174, 321, 323, 325-327, 337; precision, 321

Radio sources, closely spaced, 321; compact, 321, 322; extragalactic, 319; jets from active galactic cores, 317; supernovas, 318

Radio telescope, 185, 316, 321, 325, 326; diffraction limit, 321

Radon, endogenous lunar gas, 339

Raman spectroscopy, 201

Ranger missions, 178, 199

Rb, see Rubidium

RCS, see Reaction Control System

Re, see Rhenium

Reaction control system, oxygen/hydrogen thrusters, 28; OTV, 125; space station, 91

Reactor, accident, 463; carbon dioxide reduction, 504; column, 426; biological, 674; deuterium-helium-3, 466; deuerium-tritium, 463, 465, 466; fission, 462, 466; fission waste, 462, 463; fluidized bed, 426, 614-616; fusion, 79, 460-464, 609; gas extraction, 395; induced radioactivity to structure, 459; interior radioactivity, 465; hydrogen extraction, 395; laser power, 72; lifetime, 465, 472; loss of tritium, 464; MINIMARS, 465; nuclear, 26, 70, 245, 294, 421, 432, 459, 470, 478; orbital transfer vehicle, 37, 39; nuclear shielding, 389; plasma, 559-562; Ra, 464, 465, 466, 470; radiation damage to components, 459, 462, 465; replacement of components, 462, 465, 472; short-term radiation, 465; SP-100, 247, 478; tandem mirror, 75, 462; tokamak, 466

Reconnaissance, acquisition of global remote-sensing data, 308; Antarctica, 175; geologic, 307, 308, 311, 312; lava tube, 228; robotic lunar, 4, 308

Recycling, atmospheric, 518, 521, 673; Bios-3, 517; Biosphere II Test Module, 517; consumable, 559; fluorine, 426; importance in bioregenerative lunar base, 522; losses, 549, 550; lunar base water, 518, 551; lunar lander stage, 448; nutrients, 516, 521, 553, 556; plants, 519, 537; sewage, 532; waste, 243, 296, 297, 385, 519, 520, 548, 549, 670; waste in Biosphere II, 517; water, 177, 388, 551, 673

Reduced gravity, effects on humans, 668; lunar environment, 667

REE, abundance in plagioclase, 365; europium anomaly, 366; KREEP component, 362; rutile component, 370

Regenerative life support, 177, 293

Regolith (also see Soil), 70, 395; abundance, 275, 393; adsorption of nonpolar molecules, 615; adsorption of solar wind gases, 615; alteration by metal-fueled rocket exhaust, 433; apatite and whitlockite components, 521; Apollo 11, 190, 194; Apollo 17, 227; argon abundance, 66; beneficiation, 408, 476, 477, 610, 611, 613, 614, 616; breccias, 372; coating from sulfur-rocket exhaust, 433; cohesion, 279; compaction, 158; components, 385; concrete, 259, 493; construction material, 275; construction of shield wall, 275-279; content of useful elements, 393; correlation between ilmenite and helium-3 abundances, 668; correlation between titanium and helium contents, 609; cosmic-ray bombardment, 190; defined, 330; degassing analyses, 615; description, 195, 361; density, 71; development on ejecta deposits, 172; diffusion of implanted volatiles from grains, 615; drill core, 311; energy advantage in beneficiation, 477; energy required for heating, 613; escape of volatiles during mining, 612; evolution, 171, 174; excavation, 613, 616; extraction of hydrogen by microbial processing, 407; extraction of solar wind volatiles, 616; extraction of volatiles, 184, 228, 471, 472, 477, 480, 482, 547, 549, 610, 613-616; fines, 373, 374, 613; fusion, 71, 184, 361, 362; gas absorption, 341; gas concentrations, 184; generation, 170, 171, 212, 241; glass, 387; gravel component, 395; heat capacity, 477, 478, 613; helium abundance, 75, 189, 190, 194, 347, 349, 469, 547, 548, 610; helium-3 abundance, 189, 469, 609; helium-3 abundance with depth, 477; helium-3 content of mare, 469, 477; helium-3/helium-4 ratio, 616; history, 443; hydrogen content, 393, 394, 437, 444; ilmenite component, 611, 670; impact reworking, 373; importance to lunar colonization, 374; lack of ion-exchange minerals, 385; lack of water, 387; loss of trapped gases, 184; loss tangent, 611; lunar export, 170; lunar resource, 170, 411; mare, 189, 199, 477, 609, 613; Mare Tranquillitatis, 189; martian, 395; mass transport, 252, 277, 609, 612, 613; microwave heating, 611, 612; mining, 170, 184, 189, 195, 407, 408, 434, 470, 476, 478, 482, 547, 549, 550, 611, 612, 615, 668, 670; mobile miner, 434, 478; opening of structure by adsorbed water, 615; organic compounds, 389; penetration of helium ions, 469; penetration of mechanical drill, 409; plant-growth medium, 297; possible water source at lunar poles, 407; processing, 184, 475-478, 521, 609, 611, 613, 615; processing regolith agricultural soil, 518, 521; propellant, 407; pumping, 266; pyrolitic extraction of helium-3, 469, 478; radiation shielding, 134, 170, 177, 240, 247, 251-253, 259, 261, 264, 266, 275, 282, 285, 293, 294, 302, 408, 409, 522, 580, 581, 589, 604, 669, 670; raw material for glass production, 184, 432; raw material for special-purpose minerals, 387; relationship of grain size to helium content, 195; required amounts for helium production, 184, 189; shield wall, 275; shielding load on habitat, 252; size distribution, 609, 610; solar wind implantation, 173, 469, 477, 609; source of dust, 325; source of iron, 405, 549; source of nitrogen, 548; source of oxygen, 174, 184, 387, 411, 432, 475, 476, 479; subsurface temperature, 580, 612; sulfur abundance, 184, 432, 434; sulfur extraction, 434; tailings, 612, 616; thermal properties, 172, 589, 611, 613; thermal shielding, 580, 590; thermal storage sink, 584; thickness, 170, 185, 186, 195, 212, 216, 273, 393; titanium content, 189-195; trapped water, 393; trapping of transient-atmospheric cloud, 324; Tsiolkovsky Crater interior, 187; volatile abundance, 183, 184, 610; western Oceanus Procellarum, 161

Religion, lunar community church, 704; separation from governmental space policy, 703

Religious institutions, interest in lunar settlement, 703

Remote sensing, detection of ilmenite, 159, 160, 668; gamma ray spectroscopy, 189; ground truth, 189; large-scale reconnaissance, 307, 312; lunar, 155, 189, 190, 194, 201; lunar coverage, 199; orbital, 199; Raman spectroscopy, 202; titanium content of mare regolith, 190, 194; visible wavelengths, 203

Rendezvous, 22, 44, 56, 99, 179, 180; automated, 17, 20, 22, 23, 48, 63; Earth orbit, 6, 31, 36, 37; libration point, 102; lunar orbit, 6, 37, 42, 678; tether, 48, 56-58

Rescue, operation, 85, 151; requirement, 175; Skylab contingency, 180; support service, 399, 402; vehicle, 175

Resource, beneficiation system on mobile miner, 670; considerations, 170; development, 214, 323, 407, 409, 667, 669, 670, 697, 701; evaluation, 667, 670; exploitation, 408, 479, 643, 678, 693; exploitation on martian moons, 678; exploration, 170; exports, 150, 151, 170; extraction, 185, 409; factor in base site selection, 185, 186, 199, 267, 308, 668, 669; global distribution, 199; helium-3, 470, 475, 482, 609, 667; helium-3, terrestrial, 477; hydrogen, 393; ilmenite, 408; lunar, 4, 32, 67, 75, 76, 103, 407; lunar development organization, 699, 700; martian, 681; natural gas, terrestrial, 468; recovery, terrestrial, 409; scientific preserve, 187; storage and distribution system, 284; sulfur, 429, 434; terrestrial minerals, 245; transport, 667, 668, 670; utilization, 134, 145, 146, 151, 163, 170, 173, 311, 407; volatiles, 170, 173; water, 387

Rhenium, 371

Rille, 220-227

Risk assessment, 95, 98, 100

Rn, see Radon

Robot, assembly of spaceframes, 290; communications, 311; control, 311; deployment of geophysical instrumentation, 311; mobility requirement, 309; operational range, 311; teleoperated, 171, 172, 309; telepresence, 309

Rock, ballast in loader/crane, 177; component of regolith, 330, 371; development of fragmentation methods, 409; electrolytic smelting, 411, 412; excavation, 409; ferromagnetic signal compared to regolith, 371; field identification by spectral imaging, 309; formation conditions, 361; fusion during tunneling, 294; impact melting, 362; impediment to mining operations, 189, 194, 195; lunar types, 167, 362, 379; strength prop-

erties in vacuum, 409; use as bricks, 228; vesicularity, 220; visual recognition in the field, 309
Rocket, 78, 81; chemical, 48, 79, 677; engine, 50, 125, 677; engine blast, 135, 139, 141; equation, 3, 6, 113, 116; exhaust contamination of lunar atmosphere, 184, 185, 337, 340; expendable system, 294; fusion, 75, 76, 79; interference with optical astronomy, 183, 327, 329, 332, 334; laser powered, 70; lunar-derived, 609; lunar launch, 71; mass, 75, 78, 79; mobilization of dust, 186, 330-332; propellant, 341, 361, 374, 393-395, 407, 408, 432, 433, 475; sulfur-fueled, 432-434
Roughness, impact crater, 213; laser-altimeter measurement, 209-212; lunar surface, 139, 140, 209, 213, 216, 217; radar measurement, 195, 210; simulated, lunar surface, 216; terrestrial features, 214, 215
Rover, cost, 178; Lunokhod 2, 158; Mars, 604; mission, 70; over-the-horizon communications, 311; power, 70, 593, 594; precursor mission, 17; reconnaissance, 228; robotic, 70, 309, 401; short-range, 178; tracks, 158; unpressurized, 18
Roving vehicle, Apollo, 178, 209, 619; described in 1901, 619; lunar base, 631
Rubidium, age dating, 372; removal from water by zeolites, 388
Rusty Rock, 371

S

S, see Sulfur
Sabatier CO_2 reduction unit, 506
Safe haven, 177; lunar base requirements, 581; transporation depot, 89
Salaries, commensurability with lunar cost of living, 700; economic support for settlement of Alaska, 698; government infusion of cash in early Australia, 699; lunar employees, 700; sources of capital for lunar entrepreneurs, 700; use of Alaskan oil revenues, 698
Salyut, 333
Sample, Luna-type return, 308; lunar types, 351; rake, 309
Sample collection, 311, 374
Sample return, lunar laboratory, 351
Sample return mission, 17, 18, 150, 307, 308, 311, 312, 361
Sample return vehicle, 17
Satellite, artificial martian, 662; COBE, 317; communications, 27, 44; degradation of components, 332; Echo Program, 249; gravity-gradient stabilization, 201; lunar orbiting, 18; Solar Maximum, 329, 332; solar-power, 398, 399, 401
Saturn V, 179, 180, 683, 684; equivalent launch, 700; use of space-shuttle engines, 448
Se, see Selenium
Sea Treaty, 693; "common heritage of mankind" provision, 691; full title, 691; legal confusion with Outer Space Treaty, 693; number of ratifications compared to Moon Treaty, 693
Secondary impact, 223
Seismic activity, lunar, 231, 232
Seismic risk, lunar base, 220, 231-233; relevant factors, 232
Selenium, 431
Serenitatis region, 203
Settlement, Alaskan, 698; Antarctic, 245; Australian, 697-699; galactic, 637; lunar, 163, 261, 266, 281-283, 285, 290, 293, 296, 311, 698-700, 703; lunar autarky, 284; lunar complexities, 285; lunar environmental requirements, 175, 284; permanent lunar, 283, 401, 447; space, 237; subsurface lunar, 281
Shear, stiffness, 277; strength of building components, 270; transfer, 272
Shelter, buried, 259; collapsible, 249; compartmentalized, 285; landing site, 133, 135; meteoroid, 62; magnetic anomaly, 173; psychologically suitable, 293; storm, 252
Shielding, biological 75; collective plasma, 348-350; collimator tube, 330; concrete, 240; construction site, 259; Debye length, 348; dust, 332; exterior, 241; horizontal, 275; lava tube roof, 287; magnet, 75; radiation, 170, 333, 334, 337, 340, 385, 407, 433, 522, 669, 670; radio astronomical observatory, 163; source of secondary neutrons, 282; spacesuit, 663; structural support, 251, 266, 282; thermal, 400; vertical, 275
Shock, ground, 327; hazard, 99; impact on lava tube, 287; metamorphism of regolith, 361, 362, 371; mobilization of S and Zn, 371; reduction of spinel, 369; supernova wave, 318
Shock absorber, lunar lander, 128; Apollo LRV, 625, 626, 629
Shuttle C, 180
Si, see Silicon
Silane, 206, 432, 476
Silica, 293, 294
Silicon, alloy with iron, 412, 417, 421; amorphous, 246, 594, 596; by-product of fluorination of anorthite, 424, 426, 427; crystalline, 594; electrode in electrolytic cell, 417; reduction, 411, 412, 414-416, 418-420, 425; reoxidation to high-purity SiO_2, 421; lunar-derived, 206, 361, 374, 408, 411, 476; metal, 423; photovolatic material, 39, 398, 594, 595; purification of melt, 421; surfacing for mirrors, 421; steel, 421; tobermorite component, 387; zeolite component, 386
Silver, battery component, 148, 629; use in water disinfection, 554
Simulant, iron-rich basalt, 418; lunar regolith, 483-485, 520, 675; rhyolite, 485
Site selection, 175, 185; criteria, 217, 408; helium mining, 189, 190, 195; lava tube, 287
SKITTER, 633, 634
Skylab, 177, 180, 569, 570; carbon dioxide removal system, 504; craters on equipment, 332; exercise regimen, 661; human adaptation to reduced gravity, 668; leakage measurements, 341; space station, 237, 570; use of existing hardware, 685
Sodium, abundance in lunar pyroclastic coating, 362, 430, 432, 434; battery component, 246, 326, 431, 432; cation in tobermorite, 387; derivation from NaOH, 432; doping agent for fluorite, 427; extraction from NaF by electrolysis, 423; laser, 70; lunar atmospheric component, 338, 339; photosynthetic lighting, 539, 544; plagioclase component, 365; potential lunar sources, 669; pyroxene component, 365; reducing agent, 423-425, 427; rhyolite sand, 484; smectite saturation, 389; use in solar energy collection, 431; zeolite component, 386
Soil (also see Regolith), 29, 69, 71, 361, 369; abrasive qualities, 251; agglutinate abundance, 361, 362, 372, 374, 437, 613; aggregate in concrete, 483-487; agriculture, 518, 519; aids in moisture retention, 520; angle of repose, 140; Apollo 11, 194; Apollo 12, 419, 420, 437; Apollo 15, 437; Apollo 16, 437, 483; Apollo 17 deep drill core, 444; Apollo 17 orange glass, 437; autoreduction of Fe metal by impact, 372; ballast in loader/crane, 177; beneficial microorganisms, 532, 533; beneficiation, 395, 610; blast-barrier material, lunar, 145; buffering qualities, 531; bulldozing, 170; capillary forces, 533; cation exchange capacities, 533; cohesion, 145; compaction, 158; component of lunar cement, 489; components, 440; compositional relationship to impact melts, 362; contents of returned Surveyor 3 scoop, 331; core samples, 373, 443; correlation between helium abundance and maturity, 610; correlation between hydrogen abundance and maturity, 437, 443; correlation between hydrogen and agglutinate abundances, 438, 440; correlation between size fraction and helium abundance, 610, 611; correlation between volatile abundance and maturity, 437; cosmic-ray shielding, 361; Biosphere II, 516; definition, 361; density, 185, 251, 393, 520, 612; disturbance by Surveyor 3 landing, 331; drainage, 533; energy required for fusion, 420; enrichment of helium in ilmenite fraction, 441; erosion damage to Surveyor 3, 332; exposure age, 372; fauna in Biosphere II, 517; feedstock for electrolytic processing, 412, 421; ferromagnetic resonance, 371, 374; fertilization with waste water, 521; fine fraction, 438, 520; food production, 519, 520; formation, 371-373; fusion, 330; fusion temperature, 72; gas extraction, 344, 393, 394; gas yield, 395; gaseous exchange, lunar, 520; gourmet dining, 393; grain sizes, 372; growth medium, 297, 520; heat capacity, 395; heating for gas extraction, 341, 395; helium abundance, 194, 394; heterogeneity, 533; highland samples, 362; hydrogen abundance, 367, 393-395, 397, 437-440; hydrogen abundance at depth, 469; ilmenite distribution, 611; impact fusion, 370, 372; impact reworking and hydrogen diffusion, 437; importance for lunar base, 361, 374; ions essential for plants, 520; justification for floating foundations, 267; liming with fines, 520; lunar simulants, 483, 484, 520, 611, 624; lunar-derived fertilizer, 520; martian, 395; mass fraction as trapped gases, 341; mature layers, 373, 444; maturity, 171, 372-374, 437, 444; mechanical properties, 139, 140, 273, 326, 487; metal component, 371, 398; meteorite component, 361; microbial communities, 516, 532; micrometeoroid shield, 252; mining, 184, 395, 604, 607; mobilization by engine exhaust, 141, 144, 145; moisture, 297, 520, 522; moving, 395, 604, 607; native iron component, 371; nitrogen fixation by legumes, 522; oxygen extraction, 35, 426; particles adhering to Surveyor 3, 331; particle size distribution, 140, 142, 484, 487; permeability, 395; pH, 520; physical properties, 140, 622; plant growth, 389, 520; porosity, 158, 395; possible deficiency of plant nutrients, 520; possible effect of hydrogen content on concrete quality, 487; possible release of heavy metals, 520; prevention of water loss, 520; propellant, 206; quantity for human-equivalent composition, 393; removal for construction of large space structures, 341; reworking, 372; plant root distribution with depth, 520; SEM inspection, 487; siderophile content, 371; sieving, 395; single-domain Fe metal, 372; solar wind component, 361, 372, 374, 393, 395, 421, 437, 520, 609; sources of acidity, 519; spinel component, 369; sulfur content, 430, 433; surface-correlated sul-

fur, 429; terrestrial, 519; testing methods, 520; thermal conductivity, 395; thermal insulator, 395, 579, 589; trapping of transient-atmospheric cloud, 324; types in Biosphere II, 514; vaporization, 342; water relationships, 520; water requirement in concrete mixing, 487
Solar array, 400; advanced photovoltaic, 594; operation in continuous gravity field, 595; OTV, 37, 39; radiation degradation, 39
Solar energy, 29, 135, 599-601; collector, 613; collectors as radiation shielding, 274; collectors as roof loads, 269, 274; electrical conversion, 431; gas heating in fluidized bed reactor, 615; life support electrical requirement, 409; lunar flux, 395; lunar power source, 302, 326; production of propellants, 447; regolith heating, 395, 613; source of illumination, 302
Solar flare, research objective of Solar Maximum Mission, 332; radiation hazard, 252, 261, 275, 330, 331
Solar Maximum, information on orbital environment from retrieved parts, 325; recovery mission, 33; satellite, 329, 332
Solar power, 29, 54, 62, 404; satellite, 397-399, 401, 447, 450
Solar sails, use in Earth-Moon trajectories, 48
Solar wind, 322, 342, 347; abundance of Fe metal in regolith, 372; Alfvén speed, 348; atmospheric absorption, 342; atmospheric loss rate of Venus and Mars, 342; bombardment of Moon, 372; carbon, 338; composition, 339; concentration of gases in ilmenite, 670; containment, 615; coupling to lunar ionosphere, 339; deflection by magnetic field, 173; density, 348; depth of penetration into regolith grains, 609, 610; diffusion from regolith grains, 615; effect on lunar albedo, 168; electric field, 339, 347, 348; energy, 469; exposure time of regolith, 190; extraction from regolith, 444, 478, 482, 609, 610, 614-616; flux, 330, 339, 340; heavier elements, 339; helium, 75; implantation in regolith, 173, 194, 339, 373, 395,438, 441, 447, 469, 477, 609, 610, 615; intensity, 338; interaction with ionized cloud, 348; interaction with lunar ions, 339; interaction with lunar surface, 339; interaction with neutral gas, 339, 343; interaction with terrestrial magnetosphere, 244; interaction with unmagnetized gas cloud, 348; ions, 338, 343; lunar surface potential, 339; magnetic field, 348; major components, 337; mass flux, 339, 342; plasma source at Moon, 340; removal of gases added to lunar atmosphere, 341, 342, 347; removal of lunar transient-atmospheric cloud, 324; resistance of lunar concrete, 389; shielding provided by atmosphere, 361; source of charged-particle radiation, 330; source of helium, 170, 373, 460, 469, 475, 477; source of hydrogen, 387, 393, 408, 437; source of lunar atmosphere, 183, 337, 338, 347; source of noble gases, 411, 438, 440; source of volatiles in regolith, 477, 478, 480, 547, 609; spectrometer, 338; sputtering, 331, 338; stripping of lunar atmosphere, 342, 347-350; thermalized plasma, 340; velocity, 347
South pole (lunar), 205; base heating requirement, 582; heat loss from uncovered module, 581; heat transport and rejection system, 582, 584, 588, 589; local lunar environment, 581; possible base site, 580, 581, 589; thermal variations, 591
South Pole (terrestrial), Amundson expedition, 175
Soybeans, 525, 526, 528, 529, 538; composition, 525; crop in Biosphere II, 516; lipid content, 529, 530; optimal protein source for early lunar base, 297; part of adequate diet, 530; plasma reactor fuel, 559; potential lunar base plant, 525
Space law, 691-694; history, 693
Space station, 5, 6, 17-20, 22, 25, 29, 31, 33, 36, 37, 95, 97, 102, 116, 123, 126, 180, 246, 301, 399, 400, 475, 504, 683, 684; airlock, 580; applications of special-purpose minerals, 385; assembly and integration, 93, 604; altitude, 37; atmosphere of habitable environment, 504; automation technology, 604; avionics, 25, 29; centrifuge, 354; communications, 27; comparative cost, 175; components, 88; contamination, 99; crew, 507, 570, 603; damage, 95; data management system, 26; design, 23, 83, 87, 90-92; Earth-orbital, 133, 134, 164, 174; ECLS, 504, 505, 554; engine, 63; environment, 582; explosion hazard, 95; flight attitude characteristics, 90, 91; fueling depot, 97, 99; gas-leakage rate, 341; guidance, navigation, and control, 28; habitat lighting, 302, 303; habitation module, 249, 604; heliostat, 302; human adaptation to reduced gravity, 668, 670; import of lunar products, 472, 550, 670; insulation, 589, 590; laboratory module, 476; life support systems, 547, 550, 553; logistics module, 400; lunar base support, 83; lunar lander maintenance, 127, 128; lunar orbital, 25, 123, 133, 481, 551; maintenance facility, 125; meteoroid detector, 334; module, 184, 237, 249, 251, 294, 504, 507, 509, 580, 581, 589; momentum storage, 91; orbit, 62, 103; OTV base, 119, 123; node, 295, 580; planetary mission support, 83, 454; power system, 28, 29, 504; program, 20, 25, 26, 83, £7, 684, 688, 689; reference configuration, 296; refueling capability, 95; science, 83; software, 27; solar optics, 301; Soviet, 244; space transportation node, 103, 123; spaceframe, 289; support facilities, 83; technology, 3, 25, 26, 29, 275; thermal control, 579-585, 589; total volume, 252; waste material processing, 562; water disinfection, 553
Space shuttle (also see Space Transportation System), 237, 594; crew training, 33; design phase, 31; development, 32; external tank, 268, 394; lessons for lunar transportation system, 31, 34; main engines, 22; microgravity combustion research, 654; orbiter processing, 32; payload capability, 200; payload integration process, 34; program, 31, 33, 684, 687; reliability, 669; research in gravitational biology, 670; return of Solar Maximum Satellite components, 329, 332; mission duration, 503, 569
Space transportation, 32, 47, 54, 64, 65, 67, 81, 325, 479, 493; alternatives, 63, 65; cargo, 448; cost for lunar exports, 450, 457; costs, 32, 49-54, 64, 249, 319, 393, 398, 401, 402, 407, 447, 448, 450, 457; depot, 83-85, 88, 90-93; ferry vehicle, 450; fusion-powered vehicles, 481; infrastructure, 61, 63, 64, 67, 405; lunar, 3, 6, 31-35, 47, 61, 70, 72, 447; lunar capacity, 448; model, 44, 48, 49, 51-53, 61-64, 66, 67; node, 18, 31, 33, 101, 102, 283, 450; node at L1 libration point, 102; operating benefit, 52; operating cost, 49; operations, 31-33; performance, 54; requirements, 3, 4, 14; requirements for lunar base operation, 477; reusable system, 447, 448; scenario, 6, 9, 12, 31, 34; technology, 54, 61; terrestrial requirements, 102; use of beamed power, 399; use of lunar-derived propellant, 450, 481
Space Transportation System (also see Space Shuttle), 5-9, 13-15, 32-34, 35, 44, 47, 52, 54, 61, 64, 67, 103, 119, 123, 133, 175, 239, 250, 332, 399, 569, 616; cost, 35, 49; development, 32; launch of LDEF, 332; mission 61A, 354; mission 61B, 275; satellite retrieval, 332
Spacecraft, artificial-gravity equipped, 355; exposure to lunar environment, 329; gas leakage, 341; lunar, 31-34; lunar polar-orbiting, 308; measurement of solar wind, 339; micrometeoroid detector, 330; outgassing, 331; reference points for VLBI observations, 322; retrieved by STS mission, 332
Spacehab, 237
Spacesuit, 90, 136, 178, 660; gloves, 668; inducement of carpal tunnel syndrome, 662; mass, 663; micrometeoroid protection, 660; motion restriction, 621, 661-663; physical workload, 662; thermal environment, 660; radiation shielding, 663
Specific impulse, 6, 13, 15, 35, 56, 57, 63, 65, 66, 70, 71, 85, 121, 124, 180; arcjet engine, 42; chemical engine, 36, 48, 62, 449; cryogenic engine, 3, 4, 9, 13; effect of nozzle extension on SSME, 448; electrostatic engine, 57; fusion engine, 78; ion engine, 36, 41, 42, 54, 66; laser engine, 70, 71; lunar module, 134; Mars Transfer Vehicle, 455; nonparallel engines, 124; nuclear engine, 48; OTV, 9, 13, 36, 43, 56; O_2/H_2 engine, 39, 63; powdered aluminum, 207, 447; RCS engine, 37, 125; silane, 206; solar-electric engine, 43; sulfur-fueled rocket, 432, 433
Spectroscopy, gamma-ray, 189-193, 195, 201; lunar reflectance, 469; quasar, 317; Raman, 201, 202
Sr, see Strontium
STS, see Space Transportation System
Storage system, battery, 593; cryogenic, 97; electrochemical, 594; high-pressure gas, 596; momentum, 91; power, 403, 602
Storm shelter, 252
Strontium, 372
Structural design, lunar habitable structure, 496; planning for meteoroid impact, 283
Sulfur, 429; abundance at midocean spreading centers, 429; basis for life cycle, 433; battery component, 246, 326, 431, 432; by-product of oxygen production, 429, 434; chemical properties, 430, 432; Claus reaction, 434; combustion to sulfur dioxide, 433; compounds, 429, 610; concentration in ilmenite, 432; concentration in pyroclastic deposits, 170; concrete, 430; dietary trace element, 433; dilution in mare regolith by highland components, 429; electrical properties, 430, 431; electron shell configurations, 433; energy requirements for fusion, 430; energy requirement for production, 434; extraction from lunar materials, 429, 430, 432-434, 477, 610; fluid, 430; fluxing agent, 432; impact remobilization, 371; kinetics of release from regolith, 184; loss during pyroclastic eruptions, 429; loss during regolith formation, 429; lunar abundance, 229, 393, 429-432, 434; lunar applications, 429, 430, 433, 434; lunar production, 433, 434; lunar resource, 429, 434; mechanisms of natural lunar concentration, 429; melt content and troilite formation, 371; metabolizing organisms, 429, 433; metal-sulfate source, 430; mining, 430; mobilization by shock, 371; production of sulfuric acid, 432; propellant, 228, 432-434; radiolytic extraction from SO_2, 434; requirement for plant growth, 556; sealant, 430; sulphydryl compounds, 433; surface correlated, 429; terrestrial basalt component, 429; troilite component,

429, 430; use in fertilizer, 228, 433; use in photocells, 431, 433; use in thioelastomers, 430; volatility and formation of troilite, 371; yield relative to oxygen in ilmenite reduction, 429
Sulfur dioxide, exhaust from sulfur-fueled rocket, 433; fluid uses, 430; liquid temperature range, 431; production by burning sulfur, 433; solvent properties, 431
Supernova, extragalactic, 316; Large Magellanic Cloud, 317, 318; remnants, 316, 318; shock wave interaction with interstellar medium, 318; Type I, 318
Sun, Apollo LRV attitude indicator, 627, 628; energy source for regolith processing, 395; elevation at lunar poles, 164, 178; illumination angles for landing, 176, 620, 668; particle acceleration, 319; similar stars within 25 parsecs, 637; source of interior lighting, 302; source of primary radiation, 329, 659; source of relativistic electrons, 317; spectrum, 329; thermal exposure, 430; tracking, 301, 598-601, 668
Sun synchronous orbit, 69, 199, 639
Surface exploration, robotic, 307; cause of environmental damage, 241
Surface material, adsorption of lunar atmospheric gases, 339; photometric properties, 158
Surveying, lunar surface, 28
Surveyor, microcrater data, 332; photographs, 334
Surveyor 1, 161
Surveyor 3, analysis of returned components, 334; degradation of thermal-control coatings, 333; disturbance of soil during landing, 331; duration on surface before Apollo 12 visit, 331; dust contamination, 331, 332; end of mission, 331; evaluation of returned components, 331; interaction with Apollo 12 lunar module, 142, 331; parts returned to Earth, 325, 331; survival of bacteria on Moon, 660; television camera shroud, 330; Apollo 12 landing site, 179
Surveyor 7, evidence of suspended dust in lunar atmosphere, 344; photographs of horizon glow, 330
Surveyor missions, 199
Survival, lunar colony, 433; optimal gravity environment, 569; requirements in space environment, 547
Sweet potato, 516, 538
System integration, 27, 684; ECLS costs, 503; lunar-surface vehicle, 607

T

Ta, see Tantalum
Tantalum, capacitor failure in Surveyor 3, 331; rutile component, 370
TDRSS, see Transmission and Data Relay Satellite System
Telepresence, 309, 311
Telescope, 323, 325; adaptive optics, 327; astrometric facility, 638; autonomous operation and maintenance, 326; collimator shield, 330; contamination, 323, 325, 334; cost, 325; ground-based, 156, 159; isolation from vibrations, 327; lunar far infrared, 319; micrometeoroid threat, 330, 331; optical, 315, 185; pointing accuracy, 638; radio, 185; restoration of optical coatings, 333; system calibration, 325; thermal control, 333
Temperature, Apollo 17 site, 329; basaltic lava, 219; biomass system, 246; buffering by soil in CELSS, 531, 533; bulk gas in plasma reactor, 560; computer control, 296; control during lunar concrete curing, 490, 491; control of loss tangent of regolith, 611; control of microwave coupling with regolith, 611, 612; cool plasma reactor, 559; effects of variations on sealing techniques, 297; effects on viscosity of liquid sulfur, 430; effects on cryogenic depot, 95, 99; electron in plasma reactor, 560; extraction of volatiles from regolith, 393, 394, 547; factor in atmospheric loss rate, 339; factor in conductivity of molten silicate, 413, 414; factor in plant productivity, 544; factor in yield of regolith volatiles, 470, 477; flame, 655; freon loop, 589; fusion reaction, 75, 77, 460, 463, 465; habitat design factor, 252; increase in fusion reactor shield, 463; laser irradiated regolith, 71, 72; lava, 219; liquid helium-3, 616; lunar daytime relative to sulfur fusion, 430; lunar diurnal change, 361, 580; lunar environment, 506; lunar exospheric, 342; lunar extremes, 251-253, 287, 293, 297, 326, 579, 580, 589, 620; lunar polar, 329; lunar rate of variation, 329; lunar shaded regions, 395; lunar surface, 334, 342, 349, 584, 585, 615; mare basalt liquidus, 380; microbial growth, 506, 541; microwave heating of regolith, 614; mixing of lunar concrete, 490; module control, 581, 590, 591; operating range for fuel cell, 127; plasma, 77, 78, 79; plasma reactor, 562; radiator, 149, 584-586, 588, 616; regeneration of activated carbon, 552; regolith fusion, 71, 72, 394; regulation by natural air movement, 297; rejection, 586; requirement for lunar cement production, 497; requirement for photosynthesis, 541; sensitivity of inflatable material, 253; sink, 582-585, 588; sintering of regolith, 612; spacesuit regulation, 660; spiking in microbial growth systems, 553; stability inside lava tubes, 228, 287; subsurface, 293, 580, 589, 612; supercritical xenon, 40; superfluid helium-4, 616; tolerances of Apollo LRV, 629; transportation of lunar concrete, 490; variations with latitude, 580, 581; waste heat, 433
Temperature control, 297, 331, 333, 579; artificial intelligence, 522; Biosphere II, 514; CELSS, 544; lunar lander, 126, 135; Apollo LRV, 629
Temperature control system, 255, 584
Tether, 55-58, 61, 65, 67; angular momentum, 57, 58; applications, 55, 58; characteristics, 55; configurations, 48, 55; damage, 58; deployment, 48, 57; Earth orbital, 48, 54; electrodynamic, 66; energy, 57; length, 56-58; lifetime, 58; lunar orbital, 48; mass, 57, 58; material, 55, 57, 58; missions, 58; platform, 50, 55-57, 65-67; propulsion, 61, 65-67; reel, 57, 58; rendezvous, 56-58; repair, 58; spinning, 47, 48, 51-54, 55, 56; tension, 57; tip acceleration, 58; tip speed, 56; tip vehicle, 58; vibration, 58
Th, see Thorium
Thermal conductivity, 585; ferrosilicon, 421; polymer, 252; regolith, 71, 580, 611, 613
Thermal properties, glass composite material, 398; regolith, 172
Thermonuclear power, 459, 461
Thorium, 168; content of Mare Smythii lavas, 171; content of Smythii Basin soils, 170; enrichment in Balmer area, 172
Thrust fault, 232
Ti, see Titanium
Tilapia, aquaculture system in Biosphere II, 515; feeding on processed plant biomass, 521
Titanium, abundance in Apollo 17 regolith, 194; abundance in Flamsteed area, 193; abundance in lunar regolith, 189-195, 361, 374, 609; abundance in Mare Tranquillitatis, 191; abundance in northwestern Oceanus Procellarum 159; abundance in western Oceanus Procellarum, 160; basalt component, 216, 222, 227, 362, 369, 373, 381, 609; construction material, 240; correlation with helium content of regolith, 187, 189, 190, 609; electrolytic reduction, 419, 420; glass component, 190; ilmenite component, 159, 170, 190; lunar-derived, 408; lunar resource, 227; mare regolith classification, 190; pyroclastic component, 170, 228; pyroxene component, 365; remote detection in mare regolith, 159, 190, 191, 193; spectral absorption band, 159; spinel component, 366, 369; variety of chromite, 368
Titanium basalt, Apollo 11, 170, 189; Apollo 12, 189; Apollo 15, 189; Apollo 17, 189, 190; Luna 16, 190; Luna 24, 190; Mare Smythii, 170, 174; Tsiolkovsky, 186, 187
Tobermorite, 386
Trace element, 362
Trajectory, 33, 78; abort, 33; aeropass, 65; correction maneuver, 37; descent, 113; dust mobilized by engine exhaust, 142, 275; Earth-Moon, 48, 101, 103; Earth-Moon mission limitations, 15; free-return, 64; Hohmann transfer, 453; low-gravity aircraft, 654; lunar atmospheric gases, 339, 341, 347, 349; lunar options, 33; minimum energy, 164; multiple perigee burn, 62 opposition class to Mars, 453;
Transfer vehicle, 103, 454, 455
Transmission and Data Relay Satellite System, 27
Transport system, 255; base thermal control, 466, 579, 588, 589
Transport vehicle, lunar surface, 136
Transportation (also see Lunar surface transportation and Space transportation), advantages of inflatable structures, 250; Antarctic, 247; cislunar, 32, 61, 63, 70, 448, 449; cost, 246, 261; costs of life-support requirements, 503, 547; Earth-to-Moon costs, 549, 550, 613; gas extracted from regolith, 615; inflatable structure, 249; infrastructure, 65; interstellar, 644; lunar base requirements, 475; lunar module, requirements, 135; orbital facility, 62, 65; orbital transfer vehicle, 67; planetary surface, 245; requirements, 181; tether assisted, 61, 65-67; volume of inflatable structures, 249
Trauma, disorders caused in the workplace, 659; potential from work in spacesuit, 662
Traverse, 171-73; Apollo LRV, 629; communications, 311; geophysical measurements, 173; lunar, described in 1901, 619; teleoperated robots, 307, 311, 402
Treaty (also see Moon Treaty, Outer Space Treaty, Sea Treaty), possible constraints on lunar construction, 283; International Antarctic, 175
Tritium, diffusion in regolith particles, 615; fusion fuel, 459; parent of helium-3, 460, 477
Troctolite, 362, 365
Troilite, 429
Tungsten, 371

U

U, see Uranium

Uranium, 168, 470; energy release in fission compared to helium-3 in fusion, 470; isolation by centrifuging, 356; use of fluorine in processing, 423

V

V, see Vanadium

V, stellar luminosity class, 637

Vacuum, chamber for free-fall simulation of zero-g, 654; degradation of equipment, 99; effects on concrete, 490, 491, 497-499; effects on habitat material, 252; effects on lunar astronomical observatories, 329, 333, 334; freeze-drying waste material, 506; habitat design issue, 239, 251, 252, 268, 282; lunar, 170, 253, 409, 412, 506; outgassing of materials, 497, 499; quality at lunar surface, 315, 329, 337, 341, 342, 347; regolith adhesion, 409; spacesuit requirement, 660; use in regeneration of activated carbon, 505; uses of microwaves, 461

Vanadium, ilmenite component, 366

Vanadium pentoxide, 432

Vapor, barium interaction with solar wind, 348; catalytic ammonia removal, 246, 552; compression distillation, 246, 551; diffusion in water reclamation system, 505; distillation of water, 551; liquefaction, 96

Vapor pressure, working fluid in heat pipe, 588, 599

Vapor pressure, chlorine and iodine compared, 553; space station outgassing, 97; subcritical system, 97; transport of elements, 429, 430

Vapor cycle system, base thermal control, 585, 589

Vegetables, hydroponic growth, 674

Venus, 638, 639, 643; atmospheric loss rate to solar wind, 342; collinear Lagrange points, 642; dominant atmospheric component, 638; interstellar laser transmitter, 639; mesosphere, 638, 639; obliquity, 639; orbital laser, 639; planetary laser, 639; uniformity of gravity field, 639

Vermiculite, 389

VLFA, see Very low frequency array

Volatiles, abundance in micrometeoroids, 183; by-product of helium-3 mining, 547, 549; central separation facility, 611; coating on lunar pyroclastic material, 228, 429, 431; indigenous lunar, 170, 411; cost of extraction from regolith, 549; elements, 170, 362, 394; geologic traps, 429; lunar resource, 173, 176; lunar-derived, 429, 547, 549, 550; organic compounds in water, 551, 552; phases on Moon, 379; products of rhizosphere microorganism community, 532; production from regolith, 430, 434, 547; radioisotopes in fusion power plant, 466; replacement of lighter elements with sulfur, 429; solar wind source, 547; utilization in life support, 547, 549, 550; waste product, 550

Volcanism, 158, 160, 167, 379, 382; association with impact basins, 380; intercrater, 160; KREEP, 172; planetary, 160; postmare, 160; premare, 156

W

W, see Tungsten

Waste, biological, 228; collection and transfer in ECLS, 505; control, 245, 522; conversion, 52, 560; daily production, human, 566; deep geologic disposal, 463, 472; destruction with sulfuric acid, organic, 432; disposal, 228, 506, 556, 559; disposal ratings of fusion reactors, 462; fish, 515; freeze drying, 506; handling equipment, 566-568; hazardous, 385, 389; human, 297, 560, 562, 563, 566-568; industrial, 228; management, 238, 246, 400, 519-522, 537, 538, 542, 554, 559, 566; management facility, 399, 400; material processing, 561, 562; materials as sources of carbon, 550; methane, 432; nuclear, 463; processing, 505-507, 559, 563; processor capacity, 564; production, 521, 559, 563, 566-568; radioactive, 389, 460, 462, 465, 466; radioactive disposal, 385; radioactive repository, 463; recycling, 243, 245, 296, 517, 519, 520, 548, 549; recycling and potential for disease, 660; recycling with special-purpose minerals, 385; removal of organic compounds, 560; renovation with special-purpose minerals, 385; separation by centrifuge, 353, 356; sulfur dioxide treatment, 434; transportation, 431, 521; treatment, 516, 559

Waste heat, facility for fusion reactor, 466; low-temperature rejection, 433; lunar base power system, 505; practical uses, 505; radiation, 433; regolith fusion cell, 420, 421; rejection, 433; use for phase-change water reclamation, 505; use in ECLS, 505; use in heating ducted hot air, 245; use in power generation, 513

Waste water, definition, 520; energy requirement for processing, 597; multifiltration, 246; plumbing, 521; recycling by plant transpiration, 521; use in fertilizing plants, 521, 522

Water, 294, 296, 519, 537, 542, 549, 559; 22-GHz line, 321; abundance on Moon, 273, 283, 289, 361, 379, 411, 429, 380, 387, 393; annual replacement requirement per person, 549; aquaculture in Biosphere II, 515, 516; by-product of helium mining, 475, 477; centrifugal separation from air, 552; chemical role in concrete processing, 498; Claus reaction, 434; condensation of vapor, 539, 551; conservation by using ice in concrete mixture, 491; content of concrete, 498; content of minerals of martian satellites, 411; control in CELSS, 544; conversion to urine, 566; corrosive agent, 432; decision on potability after contamination, 554; detection of contained pathogens, 554; disinfection, 552, 554; dispersion in lunar soil, 520; effect on strength of cement, 484; effective abundance in regolith, 393, 610; electrical heating, 597, 602; electrolysis for oxygen production, 504, 549, 562; evaporation during distillation cycle, 551, 552, 648; evaporation from concrete, 490; extraction from martian soil, 395; factor in plant productivity, 544; fate in photosynthesis, 543; fecal matter as source, 554, 561, 566, 568; filtration-type recovery unit, 506; fish tanks in Biosphere II, 516; food, 507; forms of occurrence in concrete, 498; fuel-cell byproduct, 126, 127, 246; generation during reduction of ilmenite, 521, 562; heating requirement for lunar base, 597; heavy, 469; holding capacity of ground basalt, 520; holding capacity of lunar soil, 520; hydrogen equivalent in regolith, 393; hydrogen production, 432; hydrogen requirement for production, 437, 444, 470; hydrosphere of Biosphere II, 513; hygiene, 504, 552, 554; ice, 321; ice at lunar poles, 103, 164, 342, 401, 407, 411, 601; iodinated, 553; light, 466; loop, 504, 508, 547; loss, 508, 520, 549; loss from concrete, 489, 498; lunar base requirements, 176, 177; lunar-derived, 393, 547, 549; management, 126, 506, 554; mass requirement for concrete processing, 273; membrane evaporation, 551; metabolic product, 508; microbial contamination, 552; microbial control by ultraviolet irradiation, 554; NASA potable standards, 551; natural purification on Earth, 519; nutrient enhancement for plant growth, 297; outgassing from concrete, 498; outgassing on lunar surface, 324; ozone disinfection, 553; pH in lunar soil, 520; polishing, 552; possible contamination of Apollo samples, 480; potable, 246, 520, 522, 537, 549, 554, 568; potential yield of fish, 520; production, 407, 423, 432, 483, 521; production plant, 494; purification, 388, 480, 518, 519, 543, 551; quality, 508, 554, 556; radiation shielding, 259; reactor cooling, 463; reclamation, 505, 508, 551; reclamation as fuel cell product, 432; reclamation combined with waste processing, 507; reclamation from urine, 246, 551; reclamation in ECLS, 504, 505; reclamation in CELSS, 296; reclamation system, 507, 508; recovery, 507, 508, 551, 552; recovery as by-product of helim 3 extraction, 549; recovery by evaporation, 551; recovery from liquid waste, 553; recovery system, 506, 554; recovery with thermoelectric integrated membrane evaporation, 246; recycling, 177, 388, 543, 551; recycling in Bios-3, 517; recycling system, 556; regeneration, 537; regeneration in Biosphere Test Module, 517; relationship to lunar transient phenomena, 408; removal of solid wastes, 521; replacement requirement, 549; requirement for photosynthesis, 541; requirement for space travelers, 293; requirement for sulfuric acid production, 432; requirement in concrete processing, 487, 498; retention by vermiculites, 389; role in concentrating terrestrial sulfur, 429; separation, 126, 388, 582; shower, 552; shuttle potable system, 553; solar heating, 597, 600-602; solubility of silicate minerals, 519; soluble fertilizer, 521; soluble inorganic salts, 553; sterilization, 506, 554; substitution of sulfur compounds in chemical processes, 430; sulfuric acid production with sulfur dioxide, 432; supercritical oxidation in waste processing, 553; supply systems as sources of disease, 552, 600; supply to plant roots, 542; synthesis, 519; tank, 148, 296, 508; thermal control, 126, 539, 579, 580, 582, 599, 602; thermal disinfection, 553; thermochemical splitting, 432; total annual replacement requirement, 549; total organic carbon content, 554; transpiration, 522; transpiration by plants, 520, 534; transportation from Earth, 387, 602; treatment processes, 552; tritiated, 464; usage at lunar base, 520; usage for drinking, 566; use as ice in mixing lunar concrete, 490; use in hydroponics, 296; vacuum-induced loss from concrete, 498, 499; washing, 506, 552, 554; waste treatment, 246, 385; wick evaporation, 552

Water hammer, hazard during propellant transfer, 99

Water hyacinth, 521

Water vapor, 551; atmospheric distribution, 321; column density, 321; delay of radio wavefront in troposphere, 321; diffusion through membrane, 551; loss from concrete, 498, 499; masers in other galaxies, 315; radiometer, 321; recovery, 135, 551, 552; release during impact of hydrated meteorite, 183; tropospheric effects on radio astronomy, 321

Water vapor pressure, ice, 490

Wheat, 526, 529, 530, 536, 538, 541; atmospheric requirements, 528; Biosphere II, 516; composition of edible portion, 525; crop in CELSS, 525, 535; crop in plant-growth module, 556; growth dynamics, 525,

526; hydroponic, 529; production, 521, 529; water transpiration, 520; yield studies, 538, 541
Workload, increase in spacesuit, 662

X

Xe, see Xenon
Xenon, abundance in regolith, 393; ion-engine propellant, 37-44; orbital storage, 45
X-ray, absorption bands in rock, 309; binary stars, 315, 318; detection of distant galactic clusters, 316; detector, 319; diffuse background, 317, 319; identification of candidate neutron stars, 318; lunar surface environment, 327; orbital spectroscopy, 156; use in measuring Hubble parameter, 316; variability of emissions from active galactic nuclei, 317
X-ray observations, galaxy clusters, 316; objects in globular clusters, 318; stellar remnants, 318; supernova remnants, 318; synchrotron radiation, 317; supernova shock wave interaction with interstellar medium, 318

Z

Zeolites, 387, 388
Zero gravity, 99; mining operations, 411
Zinc, 412; abundance in lunar pyroclastic coating, 170, 430, 431; battery component, 148, 629; photocell component, 431
Zirconium, armalcolite component, 370; ilmenite component, 366, 370; mobilization by shock, 371
Zn, see Zinc
Zond, lunar photography, 6, 157, 159
Zr, see Zirconium

LOCATION INDEX

Alaska, 698, 700
Ansgarius Crater, 172
Antarctica, 175, 176, 237, 243, 244, 245, 246, 247
Aristarchus, 402
Australia, 402, 697-699
Balmer area, 168, 172
Balmer Basin, 168, 172, 173
Chernobyl, 464
Cone Crater, 620
Copernicus Crater, 394, 402
Crisium Basin, 172
Flamsteed region, 193
Goddard A Crater, 171
Grimaldi Crater, 157, 158, 160, 594, 654-656
Gruithuisen K Crater, 219, 223, 402
Hadley Rille, 214, 411
Halley's Comet, 339
Iceland, 215, 216, 217
Imbrium Basin, 311
Imbrium region, 189
Iridum Crater, 223
Kepler Crater, 402
Lacus Veris, 123
Large Magellanic Cloud, 317, 318
Lichtenberg Crater, 159, 160
Mare Fecunditatis, 190
Mare Frigoris, 619
Mare Humorum, 227
Mare Imbrium, 191, 222, 227, 619
Mare Marginis, 168, 171, 173
Mare Nubium, 580, 581
Mare Orientale, 156, 157, 161
Mare Serenitatis, 190, 195, 219, 222, 227, 228, 469
Mare Smythii, 163-174
Mare Tranquillitatis, 189-194, 222, 610, 611, 669
Mare Vaporum, 619
Marginis Basin, 168, 171
Marius Crater, 160
Marius Hills, 219, 225
Mars, 18, 29, 33, 47, 62, 75, 78, 79, 83-85, 88, 90, 93, 95, 96, 184, 243, 244, 342, 385, 393, 411, 447, 453-458, 475, 547, 550, 559, 569, 571-574, 619, 637-639, 647-650, 656, 657, 660-663, 667, 677-681, 686, 687, 701
McMurdo Station, Antarctica, 245
Mercury, 217, 638, 667
Meteor (Barringer) Crater, 213-215
Neper Crater, 171
Oceanus Procellarum, 155-161, 190, 191, 213, 222-227
Orientale Basin, 157, 161, 168
Peary Crater, 176, 178
Phobos, 662
Purkyne U Crater, 171
Reiner Gamma, 158
Rima Bode, 195
Ross Ice Shelf, Antarctica, 175
Runge Crater, 172
Serenitatis region, 203
Shorty Crater, 195, 444
Smythii Basin, 163-174
Smythii region, 163-174
Stillwater Complex, 380, 381
Sulpicius Gallus region, 195
Taurus-Littrow region, 190, 194, 195
Tsiolkovsky Crater, 186, 187, 668
Venus, 342, 638, 639, 642, 643

ACRONYM GLOSSARY

ΔV	Change of Velocity
A&R	Automation and Robotics
ABL	Anthropometry and Biomechanics Laboratory
AC	Alternating Current
ACC	Aft Cargo Carrier
ACS	Attitude Control Subsystem
AEC	Atomic Energy Commision
AI	Attitude Indicator
AL	Action Limit Autolander
ALSE	Active Lunar Seismic Experiment
ALSEP	Apollo Lunar Surface Experiment Package
ALSPE	Anomalously Large Solar Proton Event
AMCD	Annular Momentum Control Device
AOL	Airborne Oceanographic Lidar
AP	Agricultural Plant
APP	Astrofuel Production plant
APS	Ascent Propulsion System
APSA	Advanced Photovoltaic Solar Array
APT	Antarctic Planetary Testbed
ARC	Ames Research Center
ARCO	Atlantic Richfield Company
ASD	Advanced Solar Dynamic
ASE	Advanced Space Engine
ASO	Active Solar Optics
ASPS	Adaptable Space Propulsion System
ASTM	American Society for Testing Materials
BMC	Bone Mineral Content
BPC	Biomass Production Chamber
C&D	Control and Display
C&T	Communications and Tracking
CCGE	Cold Cathode Gauge Experiment
CDS	Command and Data Subsystem
CEC	Cation Exchange Capacity
CELSS	Controlled Ecological Life Support System
CER	Cost Estimating Relationship
CETF	Critical Evaluation Task Force
CL	Crew Lander
CL-AS	Crew Lander-Ascent Stage
CL-DS	Crew Lander-Descent Stage
CLEFT	Cleaved Lateral Epitaxy for Film Transfer
CLP	Closed Loop Processing
CLSI	Civil Space Leadership Initiative
CM	Center of Mass Command Module
CMG	Control Moment Gyro
CNDB	Civil Needs Data Base
COBE	Cosmic Background Explorer
COE	Cost of Energy
CPLEE	Charged Particle Lunar Environment Experiment
CPS	Capillary Plant Support
CSAR	Coherent Synthetic Aperture Radar
CSM	Command Service Module
CSTI	Civil Space Technology Initiative Civilian Space Technology Initiative
D	Deuterium
DC	Direct Current
DCE	Drive Control Electronics
DDT&E	Design, Development, Testing, and Evaluation
DG	Directional Gyro
DKC	Design Knowledge Capture
DMS	Data Management System
DOF	Degrees of Freedom
DPS	Descent Propulsion System
ECCS	Emergency Core Cooling Systems
ECCV	Earth Crew Capture Vehicle
ECLS	Environmental Control and Life Support
ECLSS	Environmental Control and Life Support System
EDP	Embedded Data Processor
EDS	Earth Departure Stage
EDX	Energy Dispersive X-Ray
EEO	Elliptical Earth Orbit Eccentric Earth Orbit
ELM	Earth Launch Mass
ELV	Expendable Launch Vehicle
EMPA	Electron Microprobe Analysis
EMT	Electromagntic Translator
EMU	Extravehicular Mobility Unit
EOI	Earth Orbit Insertion
EPS	Electrical Power System
ESECOM	Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy
ETO	Earth-to-Orbit
ETR	Engineering Test Reactor
ETS	Extraterrestrial Station
ETV	Earth Transfer Vehicle
EVA	Extravehicular Activity
FBR	Fluidized Bed Reactor
FDIR	Fault Detection, Identification, and Reconfiguration
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode and Effects Criticality Analysis
FMR	Ferromagnetic Resonance
FTA	Fault Tree Analysis
GCTCA	Ground Control Television Cameras Assembly
GEO	Geosynchronous Earth Orbit
GN&C	Guidance, Navigation, and Control
HDAB	Hexadecyl Trimethyl Ammonium Bromide
HI	Heading Indicator
HID	High Intensity Discharge
HLLV	Heavy Lift Launch Vehicle
HLV	Heavy Lift Vehicle
HM	Habitation Module
IF	Intermediate Frequency
IIP	Imaging Impact Probe
IMF	Initial Mass Function
IMU	Inertial Measurement Unit
IOC	Initial Operational Capabilty Initial Operating Capacity
IR	Infrared
IRAS	Infrared Astronomy Satellite
IRR	Internal Rate of Return
I_s/FeO	FMR intensity normalized to total iron content (soil maturity index)
ISA	Inertial Sensor Assembly
I_{sp}	Specific Impulse
ISY	International Space Year
IVA	Intravehicular Activity
IWWMS	Integrated Waste and Water Management System
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KREEP	Potassium, Rare-Earth Elements, and Phosphorus
KSC	Kennedy Space Center
LACE	Lunar Atmosphere Composition Experiment
LaRC	Langley Research Center
LCRU	Lunar Communications Relay Unit
LDC	Less Developed Country
LDEF	Long Duration Exposure Facility
LEO	Low Earth Orbit
LeRC	Lewis Research Center
LGO	Lunar Geoscience Orbiter
LH_2	Liquid Hydrogen
LIPO	Lunar Imaging Polar Orbiter
LLO	Low Lunar Orbit
LLOX	Lunar Liquid Oxygen
LM	Lunar Module (also LEM)
LMDE	Lunar Module Descent Engine
LO	Lunar Orbiter Lunar Orthophotomap
LOI	Lunar Orbit Insertion
LOLA	Lunar Observer Laser Altimeter
LOP	Lunar Orbital Prospector
LOTRAN	Local Transporation Vehicle
LOX	Liquid Oxygen
LRU	Line Replacable Unit
LRV	Lunar Roving Vehicle
LSA	Level of Safety Assurance

LSE	Lunar Sounder Experiment
LT	Low Titanium
LTO	Lunar Topographic Orthophotomap
LULOX	Lunar Liquid Oxygen
LUO	Lunar Orbit
LVDT	Linear Variable Differential Transformer
LVLH	Local Vertical/Local Horizontal
MACS	Modular Attitude Control System
MCC	Mission Control Center
MDM	Multiplexer/Demultiplexer
MEB	Main Electronics Box
MERI	Moon-Earth Radio Interferometer
MFV	Moon Flight Vehicle
MHD	Magnetohydrodynamic
MLI	Multilayer Insulation
MMH	Monomethyl Hydrazine
MOI	Mars Orbit Insertion
MOSAP	Mobile Surface Applications
MPD	Magnetoplasmadynamic
MPR	Mean Payback Ratio
MPS	Maximum Permissible Limit
MSFC	Marshall Space Flight Center
MSIF	Multiple System Integration Facility
MTV	Mars Transfer Vehicle
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NCOS	National Commission on Space
NEP	Nuclear-Electric Propulsion
NET	New European Torus
NI	Navigational Impactor
NIOSH	National Institute of Occupational Safety and Health
NSF	National Science Foundation
NSO	Nuclear-Safe Orbit
OAET	Office of Aeronautics, Exploration, and Technology
OAST	Office of Aeronautics and Space Technology
OMA	Operations Management Application
OMGA	Operations Management Ground Application
OMS	Operations Management System
	Orbital Maneuvering System
OMV	Orbital Maneuvering Vehicle
OPP	Oxygen Production Plant
OPWC	Oxygen Plasma Waste Conversion
OSHA	Operating and Support Hazard Analysis
	Occupational Safety and Health Administration
OTSF	Orbiting (Orbital) Transfer (Transportation) and Staging Facility
OTV	Orbital Transfer Vehicle
PAR	Photosynthetic Active Radiation
PEC	Photoelectrochemical
PHA	Preliminary Hazard Analysis
PHM	Planetary Habitation Module
PIDDP	Planetary Instrument and Definition and Development Program
PLC	Programmable Logic Controller
PLG	Prism Light Guide
PLSS	Portable Life Support System
PMAD	Power Management and Distribution
PP	Power Plant
PPF	Photosynthetic Photon Flux
PPU	Power Processing Unit
PRF	Pulse Repetition Frequency
PRV	Propellant Refill Vehicle
PSO	Passive Solar Optics
PTF	Propellant Tank Farm
PV	Photovoltaic
	Pioneer Venus
PVC	Polyvinyl Chloride
PWM	Pulse Width Modulator
PZ	Piezoelectric
R&D	Research and Development
RCS	Reaction Control System
REE	Rare-Earth Elements
RF	Radio Frequency
RFC	Regenerative Fuel Cell
RFP	Request for Proposal
RI	Range Indicator
RIG	Radioisotope Thermoelectric Generator
RLG	Ring Laser Gyro
RMP	Regolith Mining Plant
RMS	Root-Mean Square
RO	Relay Orbiter
	Reverse Osmosis
ROM	Read-Only Memory
RRS	Remote Raman Spectrometer
RSM	Radar Subsurface Mapper
RTG	Radioisotope Thermoelectric Generator
RTM	Resource Transportation Module
SAB	Spacecraft Analysis Branch
SCS	Supplemental Cooling Cart
SCUBA	Self-Contained Underwater Breathing Apparatus
SD	Single Domain
	Solar Dynamic (Generator)
SDF	System Development Facility
SDP	Standard Data Processor
SEM	Scanning Electron Microscope
SHA	System Hazard Analysis
SI	Speed Indicator
SIDE	Suprathermal Ion Detector Experiment
SLAP	Shuttle Laser Altimeter Prototype
SM	Service Module
SMRM	Solar Maximum Recovery Mission
SNR	Signal-to-Noise Ratio
SO	Solar Optics
SPF	Software Production Facility
SPS	Service Propulsion System
SPU	Signal Processing Unit
SSE	Software Support Environment
SSHA	Subsystem Hazard Analysis
SSME	Space Shuttle Main Engine
STP	Standard Temperature and Pressure
STS	Space Transportation System
SWS	Solar Wind Spectrometer
T	Tritium
TCS	Thermal Control System
TDRSS	Transmission and Data Relay Satellite System
TE	Thermoelectric
TEA	Torque Equilibrium Angle
TEI	Trans-Earth Injection
TEM	Transmission Electron Microscope
TIC	Time Interval Counter
TIMES	Thermoelectric Integrated Membrane Evaporation System
TLI	Translunar Injection
TLP	Transient Lunar Phenomenon
TMI	Trans-Mars Injection
TOC	Total Organic Carbon
TTV	Tether Tip Vehicle
TV	Television
	Thrust Vector
TVS	Thermodynamic Vent System
UF	Ultrafiltration
UV	Ultraviolet
V&V	Validation and Verification
VAT	Vehicle Assembly Tent
VAX	Virtual Address Extension
VCD	Vapor Compression Distillation
VCS	Vapor Cycle System
	Vapor-Cooled Shield
VGRF	Variable Gravity Research Facility
VHK	Very High Potassium
VHT	Very High Titanium
VIMS	Visible/Infrared Mapping Spectrometer
VIS	Visible
VLA	Very Large Array
VLBI	Very Long Baseline Interferometry
VLF	Very Low Frequency
VLFA	Very Low Frequency Array
VLT	Very Low Titanium
VMS	VAX Monitoring System
	Velocity Measurement System
VPCAR	Vapor Phase Catalytic Ammonia Removal System
WDR	Waste Disposal Rating